11/7/52

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2734

SUMMARY OF AVAILABLE HAIL LITERATURE AND THE EFFECT OF HAIL ON AIRCRAFT IN FLIGHT

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Washington
September 1952

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SUMMARY

Available information on the hail phenomenon affecting aircraft in flight has been examined. This paper attempts to coordinate the present knowledge of hail with the effect of hail on aircraft in flight and includes (1) a digest of the literature on the physical properties, the occurrence, and the formation of hail, (2) a survey of the hail effect on aircraft in flight from analyses of 57 cases of airplanes damaged by hail, (3) a résumé of hail information for the benefit of pilots, forecasters, and ground operational personnel, and (4) an annotated hail bibliography of 552 articles for use of research personnel.

INTRODUCTION

As larger and better aircraft are built, and the reliability of instrument-flying techniques is increased, more and more routine operational flights are made during adverse weather in which hail, turbulence, and other atmospheric phenomena are encountered. Flying in such adverse weather has caused the aviation interests to become alarmed at the major structural damage caused by even brief encounters with hail. Present-day transport and military airplanes are expensive pieces of equipment, and on occasion a 10- to 30-second encounter with hail has caused damage severe enough to warrant scrapping the airplane. The problem of avoiding hail areas and thus reducing the occurrences of hail damage involves methods of hail detection, elimination, and/or prediction.

Inasmuch as all of the available information concerning hail can be ascertained only by a study of voluminous literature and unpublished data from many different sources, a compilation of available information on hail is necessary for an adequate understanding of the problem. This paper has been prepared, therefore, to meet this need and includes a compilation of the literature on the physical properties, occurrence and formation of hail, a study of hail damage to airplanes, a résumé of hail information for pilot and forecaster, and an annotated bibliography of 552 articles arranged chronologically by subject. The bibliography

includes the material published up to August 1950. For completeness, the references used in the text have also been included in the bibliography.

Acknowledgement is hereby made of the kind assistance and cooperation of the following persons, whose help was invaluable in compiling this paper:

For a great deal of the material used in the bibliography

Dr. C. F. Brooks, Blue Hill Observatory, Harvard University; and
Mr. Malcolm Rigby, Meteorological Abstracts and Bibliography, American Meteorological Society.

For an appreciable amount of data on hail damage, much heretofore unpublished

Mr. H. T. Harrison, Jr., United Air Lines, Inc.;
Messrs. A. F. Merewether, L. W. Armstrong, and R. Keefe, American Airlines, Inc.;
Mr. John Moore, Directorate of Flying Safety, U.S. Air Force; and
Mr. Richard J. Roth, Crop-Hail Insurance Actuarial Association.

For material on the theory of hail formation and current research on hail

Lt. Col. Robert Bundgaard, Air Weather Service, U.S. Air Force;
Dr. Vincent J. Schaefer, General Electric Research Laboratory;
Dr. Helmut Weickmann, Evans Signal Corps Electronics Laboratory, U.S. Army; and
Dr. E. J. Workman, New Mexico School of Mines.

COMPILATION OF HAIL LITERATURE

This section presents information concerning hail phenomenon from the literature. In some cases the information is presented without comment, and no attempt is made to evaluate the reliability of one set of data over another set of data. The physical properties of hailstones are given with some comment as to the average properties of the stones as found on the ground. The frequency of occurrence of hailstorms is discussed. Theories concerning the formation of both hailstorms and hailstones are also covered.

PHYSICAL PROPERTIES OF HAILSTONES

Definitions

Although hail in its larger forms is readily identifiable, it becomes increasingly more difficult to identify in its smaller forms. Several of the hydrometeors that are similar to hail of the smaller variety are known as small hail, sleet, snow pellets, and snow grains. In order to identify hail from the other types of hydrometeors, the following definitions, normally used in the United States and given in reference 1 by the U.S. Weather Bureau, are used in the present paper:

"HAIL - Ice balls or stones, ranging in diameter from that of medium-size raindrops to an inch or more. They may fall detached or frozen together into irregular, lumpy masses. They are composed either of clear ice or of alternating clear and opaque snowflake layers. Hail often accompanies thunderstorm activity. Surface temperatures are usually above freezing when hail occurs. Determination of size will be based on the diameter, in inches, of normally shaped hailstones."

The present paper is primarily concerned with this type of hail.

"SMALL HAIL - Semitransparent, round or conical, grains of frozen water. Each grain generally consists of a smaller grain of soft hail as a nucleus, surrounded by a very thin ice layer, which gives it a glazed appearance. The grains are wet when they fall at temperatures above freezing. They are not crisp or easily compressible, and do not generally rebound or burst even when they strike hard ground."

"SLEET (ICE PELLETS) - Transparent, more or less globular, hard grains of ice about the size of raindrops, that rebound when striking hard surfaces. Its fall may be continuous, intermittent, or showery."

"SNOW GRAINS (GRANULAR SNOW) - The solid equivalent of drizzle. They take the form of minute, branched, star-like snowflakes, or of very fine simple crystals. At times they have the appearance of rime. They occur under meteorological conditions similar to those of drizzle, except that the temperature is lower."

"SNOW PELLETS (SOFT HAIL) - White, opaque, round or occasionally conical kernels of snow-like consistency, 1/16 to 1/4 inch in diameter. They are crisp and easily compressible, and may rebound or burst when striking hard surfaces. They occur almost exclusively in showers."

In the preceding definitions of hail and small hail no clear line of demarcation between the two is given. References 2 and 3 indicate that there is a discrepancy in the definition of small hail. Reference 2 gives the demarcation as 0.2 inch in diameter whereas reference 3 does not include the small-hail classification.

Composition

Although the usual hailstone consists of alternate layers of clear and opaque ice, with as many as 20 to 25 concentric layers, hailstones have been observed which were composed entirely of either clear ice or opaque ice. Some hailstones with the usual alternate shells of clear and opaque ice have a core of supercooled liquid water. A core containing an air bubble has occasionally been observed, but this type is rare. Because of the wide variance in the composition of the hailstones, no definite appearance of hailstones can be assured, although within a single hailstorm the composition of the stones varies only slightly. Hailstones may have a variety of extraneous matter contained in them; muddy and black hailstones have been reliably reported.

During the 1950 hail season at Denver, H. T. Harrison, Jr., manager of Weather Service for United Air Lines, Inc., analyzed the structure of

a few of the stones which fell during a storm on September 16th. The results of this analysis are presented below:

Size (diam.) (in.)	Number of samples	Type of core (a)	Number of samples								
			Number of layers								
			3	4	5	6	7	8	9	10	11
$\frac{7}{8}$	9	9 opaque	2	0	2	0	3	0	1	0	1
1	10	5 opaque, 3 clear, 2 mixed	2	2	3	1	0	1	1	0	0
$1\frac{1}{16}$	6	5 opaque, 1 clear	0	1	3	0	1	1	0	0	0
$1\frac{1}{4}$	2	1 opaque, 1 clear	0	0	0	1	1	0	0	0	0
Total	27		4	3	8	2	5	2	2	0	1

[a]Nineteen of the 20 stones with an opaque core had an odd number of layers, whereas the 5 stones with a clear core all had an even number of layers.

Specific Gravity (Density)

Since a hailstone may be composed entirely of clear or opaque ice, the limits of its specific gravity are between 0.25 and 0.92. Little information concerning the actual specific gravity of hailstones is available; therefore, various sources have been used in the present paper to determine a representative value. The specific gravity of ice formed on airplanes has been found to range from 0.70 to 0.85. Reference 4 gives the specific gravity of ice collected at Mt. Washington as ranging from 0.45 to 0.92. In theoretical papers on hail in which an exact expression is required for calculations, specific gravities between 0.6 and 0.8 have been chosen. From a consideration of these values, the average specific gravity is evidently close to 0.7, and this value has been used when necessary in calculations presented in this paper. Inasmuch as density and specific gravity are numerically equal in the metric system, specific gravity has been used herein as specific gravity has a further advantage of being dimensionless.

Shape

Most hailstones have one of the following three shapes: spherical, conical, or discoidal. The spherical shape is by far the most common, especially when the hail is small. Some hailstones have also been observed in the shape of spheroids, pyramids, dumbbells, and so forth,

or as jagged, irregular lumps of ice. Furthermore, large hailstones of any shape may have many irregularities and protuberances. Numerous accounts of hailstones of unusual appearances can be found in the Monthly Weather Review issues of the first three decades of the present century.

Figure 1 is presented as an example of some of the typical forms that hailstones may take. Figure 1(a) is a reproduction of a photograph which appears in reference 5. These stones fell at Washington, D. C., on April 28, 1938. The conical shape is readily discernible. The stones of figure 1(b) fell at Potter, Nebraska, on July 6, 1928, and are reproduced from reference 6. The stone on the extreme left had the appearance of being formed by the amalgamation of two smaller stones. The stones shown in figure 1(c) fell in Czechoslovakia on June 13, 1946. This photograph is reproduced from an unpublished manuscript by Dr. Helmut Weickmann. The stones in the lower right corner of the photograph appear to be composed of one or two alternating layers of clear and opaque ice. The alternating layers in these stones are thicker and therefore more noticeable than in the usual stone.

Size

With a few exceptions, there have been no systematic observational programs for determining hailstone sizes. Although many reports have been published describing the size of the largest hailstones, the structure of hail, the amount of crop loss due to hail, and so forth, very little has been written on the hail size distribution within hailstorms. Observers tend to report the largest and moderate sizes of hail but fail to record the smaller sizes; therefore, the average compiled from these reports may be larger than is actually the case.

The most common sizes of hailstones measured on the ground at various regions have been analyzed by Eliot (India), Ruby (France), Hann and Süring (Central Europe), and Humphreys (United States), and have been found to be (reference 7):

Region	Most common size (diam.)	
	(in.)	(cm)
India	0.2 to 1.2	0.6 to 3.0
France	0.2 to 0.8	0.5 to 2.0
Central Europe	Up to 1.2	Up to 2.0 or 3.0
United States	0.5 to 0.7	1.2 to 1.8

Eliot's study of 597 hailstorms in India gives the following indication of hail size frequency:

Hail size (diam.)		Frequency (percent)
(in.)	(cm)	
Up to 0.2	Up to 0.6	27
0.2 to 1.2	0.6 to 3.0	51
Above 1.2	Above 3.0	22

After a study of 7 years' records, 1931 to 1937, United Air Lines, Inc. (reference 8) found that hailstones of walnut size (1 in.) or larger occur in about 1 out of 800 thunderstorms in the area between Chicago and Denver. The frequency of hail half this size is several times greater. During the period studied, there were 136 storms in the United States which produced hailstones 1 inch or larger; of these stones, 50 percent were 1 to 2 inches, 40 percent were 2 to 3 inches, and 10 percent were 3 inches or larger.

Accounts of storms of large hailstones are scattered throughout the literature. Apparently, the largest hailstones ever recorded in the United States are those which fell at Potter, Nebraska on July 6, 1928 (reference 6). Several of these stones are shown in figure 1(b), the largest stone being on the right. This stone measured 5.4 inches in diameter and weighed 1.5 pounds.

Hailstone size in relation to weight (spherical shape assumed) is shown in the following table:

Hail size (diam.)		Weight (specific gravity 0.7)	
(in.)	(cm)	(lb)	(g)
0.5	1.27	0.0017	0.75
1.0	2.54	.103	6.01
2.0	5.08	.11	48.05
3.0	7.62	.36	162.17
4.0	10.16	.85	384.4
5.0	12.70	1.66	750.8
6.0	15.24	2.86	1297.0

Temperature

Inasmuch as the temperature of hailstones at the altitude of formation has not been determined because of measurement difficulties, other means must be used to estimate the probable temperatures. Temperatures inside hailstones, determined immediately after the stones strike the ground, have been found to be at, or less than, 0° C, and often between -5° C and -15° C. If the average atmospheric temperature aloft during hailstorms is considered, the temperature of hailstones at altitudes from 10,000 to 20,000 feet should generally be between the limits of 0° C and -20° C, although in some instances and at higher altitudes the temperature of the stones may temporarily be lower than -20° C.

OCCURRENCE OF HAILSTORMS

The climatology of hail is an important phase of the subject, since the knowledge of where and when hail occurs has a direct bearing on the effect of hail on airplane operation. This section discusses the occurrence of hailstorms in respect to local ground, geographical, hourly, seasonal, and vertical distributions of hail and, also, the duration of hailfall.

Local Ground Distribution

In agricultural areas where crops are damaged by hail, an observer may analyze the local ground distribution of particular hailstorms. Using this method, several investigators have studied the hail pattern on the ground; however, the instantaneous pattern on the ground or aloft has never been thoroughly investigated. Since the hailstorm nearly always has a movement with respect to the ground, the hail pattern produced on the surface has a length proportional to the speed of the storm and to the length of time the hail falls. On the other hand, the width of the hail area as seen on the ground is a direct measure of an instantaneous storm area.

Several studies of the local ground distribution of hailstorms have been made. Frank J. Phillips (reference 7), after studying the areas of hailstorms in Missouri, stated that hail appears in narrow bands ranging from 2 to 400 feet in width and up to a half mile or more in length. This study was a detailed one of only a few storms. Prohaska (reference 7) made a study of 113 European hailstorms having a length of 12.5 miles or more and found that the most common width ranged from 5 to 6 miles. Bühler (reference 9) found from a study of damaging hailstorms at Württemberg over a 60-year period (1828 to 1887) that the smallest area damaged was 6 square miles and the greatest, 124 square miles.

The most complete study of hail areas to date was made by Hoyt Lemons (reference 10). This study included 2105 hailstorms that occurred in the United States over a 14-year period (1926 to 1939). The most common width was found to be 1 to 2 miles; however, the width varied considerably and ranged from a few yards to 75 miles. Figure 2 shows the results of Lemons' study of hailstorm widths.

Because of the restricted nature of the analyses made by Phillips, Prohaska, and Bühler, and because of the greater number of storms studied by Lemons, the latter's data seem to be the most representative.

Geographical Distribution

Although the occurence of hail is generally associated with the occurrence of thunderstorms, the geographical distributions of the two are not the same. In general, the world-wide pattern of hail occurrence seems to be characterized by greater frequency in the "continental interiors of middle latitudes, diminishing seaward, equatorward and poleward" (reference 11). In order to provide the material for a detailed comparison of the thunderstorm and hail distribution patterns in the United States, the Weather Bureau evaluated 40 years of records (1904 to 1943) from 217 first-order stations. The results of this analysis are given in reference 12. Charts are included showing the average number of days with hail compared with days with thunderstorms, annually and monthly. These hail distribution charts include the "small hail" of the West Coast and, as a result, produce a rather significant looking maximum in that region, especially in the Pacific Northwest. Figures 3(a) and 3(b) show the average yearly distributions of hail and thunderstorms, respectively, over the United States. Figure 3(a), which does not include the Pacific Coast small hail, is taken from reference 13. (The small hail is of little concern to aviation operation.) Figure 3(b) is taken from reference 12.

The following table is given to show the greater frequency of hail in the United States and the decreased frequency northward, southward, and seaward:

Location	Mean annual frequency of hail days
Galveston	0.9
New York	1.0
Milwaukee	2.0
Cheyenne	9.4

Lemons (reference 11) also made a comprehensive study of hail occurrence in low and high latitudes where there has been a lack of observational data. In very low latitudes hail is infrequent; however, at some subtropical localities the frequency of hail is as great as at middle latitudes, although usually smaller in size. Hail occurs more frequently and is more destructive at the higher ground elevations in low latitudes. In high latitudes hail may occur at both high and low elevations and, in many cases, the so-called hailstones are actually snow pellets. Hail at high latitudes is usually associated with frontal rather than thermal thunderstorms. The size of the stones is generally small and, because of the small concentration of people and crops, hail is of little consequence economically.

In the middle latitudes, which include the United States, appreciable data are available from crop damage. The magnitude of the annual hail damage can be realized from the following estimate of damage to three of the 1947 crops in the United States:

Crop	Damage
Wheat	$118,617,000
Corn	85,996,000
Tobacco	20,470,000

Statistics released by the Crop-Hail Insurance Actuarial Association of Chicago, based on claims for losses inflicted by hail (reference 14), are are in reasonable agreement with the U.S. Weather Bureau maps of hail distribution (fig. 3(a)). Figure 4, which shows the 1950 crop-hail insurance rates (50 percent of which are used in paying claims), is based on these statistics. This figure is published here through the courtesy of the Crop-Hail Insurance Actuarial Association. When the insurance data are compared with the Weather Bureau statistics, discrepancies are found in certain small sections of the country. Several factors lead to these minor discrepancies, the chief of which is the difference in the methods of observations. The Weather Bureau statistics are based only on reported hailstorms at first-order stations, damage notwithstanding, whereas the Crop-Hail statistics take into account only those hailstorms which cause damage to crops and for which losses are claimed.

Another important consideration in determining the actual distribution of hail is the ratio of area to point frequency of hail occurrence. Although present statistics are based on point frequencies, it appears that area frequency would be more accurate. Alfred Angot (reference 9) of the French Meteorological Service estimated that an ideal reporting network for obtaining realistic area frequencies of hail should be one station for each 4 square miles. Nothing approaching such

a network, however, has ever been established. A. L. Shands (reference 15) of the U.S. Weather Bureau worked out a theoretical ratio of area to point frequency for the state of Iowa by using a network of 150 cooperative weather bureau stations. Results indicated a ratio of 15 to 1, which means that, if average point frequency of hail in Iowa is 4 days a year, hail should be found somewhere in the state about 60 days per year. During 1949, United Air Lines (reference 16) made a study of hailstorms in the Denver area. A total of 11 observation points in this area were used and the results were compared with the observational data released by the Weather Bureau station at Denver. During this period, 33 hailstorms were reported from the United Air Lines observational network, and the comparison gave an 11 to 1 ratio of area frequency to point frequency. Further observations with twice as many reporting points in the network were made in the Denver area during the 1950 hail season; however, the results are not yet available.

Shands also points out that when a single station in Iowa observes hail on only 1 day out of 12 days during which thunderstorms occur, the ratio builds up to almost 1 to 2 when the occurrence of hail over the state is compared with the occurrence of thunderstorms over the state. This ratio is comparable to the hail-thunderstorm ratio of 1 to 14 which was observed at the Denver Weather Bureau station during the 1949 hail season and the ratio of 1 to 1.3 reported by the United Air Lines observational network in the Denver area.

Although the Weather Bureau and the Crop-Hail Association present the most reliable statistics available on the distribution of hail in the United States, these statistics must be applied with discretion because of the limitations of the data upon which these statistics are based. Available information on the ratio of area to point frequency further substantiates the fact that hail distribution charts are good for comparison purposes but should not be used specifically for any one area.

Hourly Distribution

It is generally agreed that 50 percent of all hailstorms occur between 1400 and 1800 LST (local standard time) and less than 10 percent, between midnight and noon.

In 1944, United Air Lines (reference 17) reported that in the central and eastern United States large hail falls mainly in showers between 1200 and 2100 LST and is especially frequent between 1500 and 1800 LST. During the 1949 study of hailstorms in the Denver area (reference 16), the average time of occurrence in May was found to be 1300 LST but shifted to 1430 LST by September.

Lemons (reference 10) in a study of the hourly distribution of 2355 hailstorms in the United States over a 14-year period (1924 to 1939) has reported that one-third of all hailstorms that damaged crops occurred between 1600 and 1800 LST and two-thirds, between 1300 and 1900 LST. Figure 5, showing the hourly distribution of damaging hailstorms, is taken from reference 10.

Seasonal Distribution

Hail in the United States is generally a warm-season phenomenon, occurring chiefly in the spring and summer (reference 12 and 18). The country may be divided into three regions of hail occurrence: (1) the East and South, including the Gulf States, (2) the Interior from the Ohio Valley westward, including the Great Plains and the Rocky Mountains, and (3) the Pacific Coast area.

Early in January the light hail area begins in the South and gradually spreads northward. Most of the East and South have some hail from mid-March to mid-June, then there is a gradual waning of activity, especially in the coastal areas. A hail-free area appears along the Texas coast early in the year. This area moves northward and eastward until most of the inland area is free of hail by mid-October; however, some small areas with rugged terrain continue to have hail after October.

The Interior is characterized by a warm-season northward development and spread of hail activity. Beginning in February the hail area starts a northward and eastward movement from the southern Plain States until late in April, then it spreads north-westward over the Plains and Rockies until late June. By late September, southward recession and lessening intensity is evident. Early in October a hail-free area appears in Montana. This area begins a southward movement, fanning out in the north, until by early January it extends from Canada to Mexico.

Hail in the Pacific Coast area is chiefly a cool-season phenomenon. Even in the winter the frequency of real hail is low. Most of the hail in the West Coast States is small hail and does little damage.

Figures 6(a) and 6(b), respectively, show the months of maximum hailstorm and thunderstorm frequencies in various sections of the United States. From a comparison of the two figures it can be seen that in most sections the month of maximum frequency of hail is earlier than the month of maximum frequency of thunderstorms. These two figures were taken from reference 12, although figure 6(a) was modified slightly in order to eliminate some of the very small monthly hail variations in the northeast.

Vertical Distribution

Very little data are available on the vertical distribution of hail aloft. The Thunderstorm Project (reference 19), although not carried out in the areas of maximum hail occurrence, has shed some light on the subject. During 551 cloud traverses by airplanes in thunderstorms and potential thunderstorms over Florida in 1946, hail was reported in 22 cases, or 4 percent of the traverses. In Ohio in 1947, 812 cloud traverses were made through thunderstorms and hail was reported on 51 occasions, or 6 percent. In almost all of the cases where hail was encountered, the stage of development of the cloud could not be classified. Table I, taken from reference 19, gives a detailed breakdown of the hail intensities and the flight altitudes at which hail was encountered in Florida and Ohio.

Hail was encountered most often at 16,000 feet over Florida, and at 10,000 feet over Ohio. It appears that the region of hail in any storm and the duration of hail in that region are relatively small. When hail was present in a cloud, it was found in only 25 percent or less of the traverses through the storm at the level of its occurrence. Seldom was hail found at more than one or two levels in the same storm. It therefore appears that hail occurs in very narrow bands within thunderstorm clouds and occurs less frequently above 20,000 feet.

Duration of Hailfall

Most authors seem to be rather reluctant to commit themselves on the duration of hailfall, and when a commitment is made the phraseology is ambigious; wording such as "less than an hour" and "a few minutes" is typical. Phillips (reference 7) found that the most common duration of hailstorms in Missouri was only "several minutes". Eliot (reference 7), who considered a large number of hailstorms in India, concluded that in most cases hail lasted 30 minutes or less.

Although frequently hailstorms are reported for periods much longer than 15 minutes, the average duration of a hailstorm in the United States is about 15 minutes at any particular point. Figure 7, taken from reference 20, shows hail 2 feet deep which fell at Trinidad, Colorado, on June 14, 1937. It is highly improbable that this large amount of hail could fall in a period as short as 15 minutes, since it is roughly equivalent to 12 inches of rainfall. Numerious reports of hail a foot or more deep are also available.

FORMATION OF HAIL

Theories on the formation of thunderstorms (potential hail-producing storms) are few in number, rather well-developed, and in basic agreement. The situation in regard to theories on formation of hailstones is quite different. Many theories exist postulating different physical processes, but no one theory has been found to be completely satisfactory. The purpose of this section is to give an account of some of these theories on hailstorm and hailstone formation.

Hailstorm Development

Hailstones fall almost exclusively from convective-type clouds, although hail does not fall from all thunderstorms. The mechanism by which thunderstorms develop has been well-established, and numerous references describing this mechanism are available in textbooks and elsewhere. The most complete and recent report on thunderstorms is reference 19. Although the mechanics of thunderstorms has been established, the problem as to which thunderstorms produce hail is known in only the broader sense. In general, the more violent storms produce hail.

Detailed surface and upper air information is necessary to understand the cause of these storms. The chief factor involves atmospheric instability, a thermodynamic condition in which vertical currents, once induced, are favored and accelerated. The degree of instability and the vertical extent determine the magnitude of the vertical currents; heating and frontal or orographic lifting initiate these currents. As the air ascends it cools adiabatically and, if sufficient moisture is present, it condenses and forms clouds. With additional lifting, precipitation develops. In most cases the precipitation does not develop until the top of the cloud extends at least above the freezing level. The life cycle of the thunderstorm cell may be divided into three phases: the building, the mature, and the dissipating stages. It is thought by many that hail, if present, occurs late in the building stage or early in the mature stage.

Theories of Hailstone Development

Although numerous theories are available concerning the formation of hailstones, most theories are limited to an explanation of only a particular method of hail formation. William Ferrell in 1885 theorized that whirlwinds of tornadic character could form and hold heavy hailstones in the air until their final fall to the ground. Bigelow later contradicted this theory, as it did not explain how the centrifugal force of the hailstone could be counteracted in the tornado. Both Hann and Kassner have

proposed theories for the formation of hailstones. Hann suggested that they are formed by the explosion of larger spherical stones, whereas Kassner suggested that small precipitation particles of ice grow conical by accretion of supercooled cloud droplets on their bases. (See reference 21.)

Formation in ascending currents.- "Elementary Meteorology" (reference 22), published in 1894, included much general information on thunderstorms and hail. Davis suggested that hail is produced in active convectional storms by the freezing of raindrops that have been formed at low levels and carried upward by the central ascending currents to altitudes of very low temperature; the frozen raindrops, becoming coated with a layer of snow, increase in size until they fall through the less active currents. This process may be repeated several times. Humphreys (reference 23) supports this theory and has made it the most widely accepted theory of hail formation.

Knowing the drag of a sphere of a given size, Humphreys (reference 24) computed the magnitude of the vertical velocity necessary to sustain hailstones (specific gravity 0.7) of the same size, as follows:

Diameter of hailstone (in.)	Velocity necessary to sustain (m/sec)
1	25
2	35
3	49
4	83

The velocities given in the table appear reasonable, especially those which sustain the smaller hailstones. Grimminger (reference 25) carried the analysis of Humphreys further by taking into account the effect of turbulence in the air stream. (This so-called fine-grain turbulence is not the large-scale turbulence usually considered by meteorologists.) The drag of a sphere is partially affected by the intensity of the fine-grain turbulence. Grimminger calculated that, with a great amount of turbulence, the speed of the upward current necessary to sustain the hailstone is roughly double the speed under normal conditions.

Some theoretical work has been done to determine the upper limits of hailstone size. E. G. Bilham and E. F. Relf (reference 26) based their investigation on aerodynamic considerations of the drag of a sphere in vertical currents. The relation between the terminal vertical velocity and hail diameter was deduced from the values of the drag coefficient (obtained from observations on spheres towed by airplanes) and a plot of the data resulted in an S-shaped curve which indicated that, as the

terminal velocity increases, the hail diameter increases, decreases, and then increases again. (This S-shaped curve results from the sharp change in the drag coefficient of a sphere at a Reynolds number near 350,000.) Since the second part of the S-curve represents unstable conditions and since the third part would require vertical velocities above practical limits, it was determined that the first part of the curve represented the true theoretical range in the relationship between terminal velocity and hail diameter. The theoretical upper limit of hailstone size in vertical currents was found to be about 5 inches in diameter and the maximum weight, about 1.5 pounds. This upper limit is in good agreement with the size of the largest stones found on the ground.

Formation during descent only.- In 1938 T. E. W. Schumann (reference 27) pointed out that, although vertical currents aid the formation of hailstones, it is not necessary that they be of sufficient magnitudes to lift the hailstones during formation or even to suspend them. Once a solid core is formed to which other cloud droplets or raindrops may adhere, such a particle accumulates ice on descent. The amount of ice accumulated is dependent on the length of fall (time) and the liquid water content of the air. For example, Schumann has calculated that, with a vertical wind velocity of only 8 meters per second and a concentration of water of 13 grams per cubic meter, a hailstone 3.2 inches in diameter (specific gravity 0.6) can be formed in falling from 29,500 to 13,000 feet (9 to 4 km). Schumann points out that, although a water concentration of 13 grams per cubic meter is above average, it is not uncommon.

E. Gaviola and F. Alsina Fuertes (reference 21) also are of the opinion that upward currents are not a necessity in the formation of hailstones. These authors assumed that hailstones form initially from cloud particles of supercooled water droplets and ice or snow crystals. After initial formation a hailstone can grow, while falling only, by successive wetting and solidifying as it collides with other cloud particles. The initial stone, while it is wet, grows by accretion of snowflakes, but it soon becomes solid because the liquid phase gives up its latent heat to bring the temperature of the snowflakes up to 0° C. Once the hailstone is solid, no more snowflakes adhere to it; it now has to collide with supercooled water droplets to become wet again. When the hailstone becomes wet, a clear ice layer is formed, which grows as long as colliding supercooled droplets predominate over ice and snow crystals. When the hailstone again becomes solid, an opaque layer forms. The alternating layers of the hailstone are thus produced. By assuming an absolute humidity of 10 grams per cubic meter, the authors made calculations which show that a hailstone would take about 5 minutes to fall from 26,000 to 13,000 feet (8 to 4 km) through an atmosphere at rest, and would grow into a 2-inch hailstone.

Formation in convectional vortex rings.- Robert E. Horton (reference 28) has indicated that hail may form in convectional vortex rings. The moisture within the vortex ring has a circular movement around the ring, such that ascending and descending currents of moist air result. No explanation, however, is given of the manner in which accretion occurs when hailstones grow in size or of the temperature of the hailstones relative to the surrounding air. It is assumed that the hailstones form a clear ice layer on ascent and an opaque layer on descent. Atmospheric vortex-ring cloud systems occur in conjunction with violent convection storms and, when these systems occur, the ascending moist air is concentrated within the vortex rings. Conditions favorable for the formation of these convectional vortex rings are also shown to be favorable for the production of hailstones. The vortex-ring condition produces hailstones of uniform size and layers and has sufficient ascent velocity to sustain large hailstones. The vortex-ring clouds are likely to produce large hailstones, whereas the tubular-type clouds are likely to produce hailstones of various forms, sizes, and different internal structures, but generally of a small size.

Formation similar to icing on aircraft.- Dr. Helmut Weickmann* has developed theories on the formation of hailstones based on icing research experiments conducted in Germany during World War II. The original experiments were conducted to investigate the meteorological conditions associated with ice formation on aircraft; in later years Dr. Weickmann used the same data to arrive at his theories on hail formation.

Weickmann proposes the theory that opaque ice may result from two different processes: first, by individual crystallization of cloud droplets at the surface of the falling hailstone, and second, by air bubbles becoming imbedded in water which freezes quickly. The essential condition for the formation of clear ice involves the freezing process which must progress slowly enough to allow coagulation of the deposited droplets before freezing. Since the rate of crystallization is slow near 0° C and increases with decreasing temperature, the formation of clear ice near 0° C and the formation of opaque ice at lower temperatures can be expected. With a high liquid-water content in the clouds, however, the rate of crystallization may be slow even at low temperatures.

The apparatus used in the aircraft-icing research conducted by Dr. Weickmann is shown in figure 8. Figures 9, 10, and 11 indicate typical samples of ice collected during the course of this investigation. The

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*Dr. Weickmann is now employed by the U.S. Army Signal Corps at the Evans Electronics Laboratory, Belmar, New Jersey. During 1950 he revised and translated into English his original paper on "The Formation of Hailstones" and has kindly sent a copy of the revised paper to the authors.

hailstones of figure 1(a) show a similarity to the ice deposits of figures 9 and 10, in that they both have a conical shape and an opaque appearance. Similarity is also noted between the hailstones of figure 1(c) and the ice of figure 11; both have wart-like irregularities and a predominance of clear ice. The clear-ice appearance is caused by the exceedingly slow rate of crystallization which allowed the cloud droplets to coagulate before freezing occurred; the slow rate of crystallization is a result of the high moisture content and near-freezing temperature.

Contribution from nucleation experiments.- It has been ascertained experimentally that a cloud containing water droplets of below-freezing temperature can be converted into an ice-crystal cloud by the addition of either dry-ice pellets or silver-iodide crystals to the cloud. Project CIRRUS, headed by Drs. Irving Langmuir and Vincent Schaefer and sponsored by the Armed Services, has been conducting basic research on cloud physics since 1947. References 29 to 36 include most of the work done on this project pertinent to the hail problem.

Dr. Langmuir, Dr. Schaefer, and others believe that destructive hailstones form in certain thunderstorms when a minimum of sublimation nuclei is present. Preliminary data show that the number of sublimation nuclei in the atmosphere is extremely variable - from 100 to 1,000,000 per cubic meter. Future experimental investigations may prove the theory that destructive hailstones $\left(\text{over } \frac{1}{2}\text{-inch in diameter}\right)$ form only in clouds where the nuclei count is low, say below 5,000, whereas seeding of these clouds to obtain only rain might require a higher count, 20,000 or more. (The numbers of nuclei given here are for quantitative comparison only.) If this theory can be proved, it would be comparatively easy to increase the nuclei in potentially dangerous hail areas to an amount which would eliminate destructive hail and still not cause abnormal rain.

A cloud-seeding project (reference 37) has been in operation in the Rogue River Valley section of southwestern Oregon since May 1949. (The techniques used in this project are similar to those advocated by the personnel of Project CIRRUS.) Hail is reported to have damaged up to one-half the fruit crops in the Rogue River Valley in each of the 38 years previous to 1949, with one exception. So far as is known, hail has not fallen on the project area since the project has been active.

The operators of this project, Messrs. Harvey Brandau and Eugene Kooser, believe, as do Drs. Langmuir and Schaefer, that the greater the number of ice crystals within clouds, whether naturally or artificially formed, the less chance there is of hail forming. The "overseeding" method, consequently, is used in this project. The nature of the seeding material and the method of application to the cloud has not been released as yet. The investigators agree with others that hail is formed during

the formative and transition stages of a thunderstorm's development and in the portions of supercooled clouds having temperatures between -5° C and -39° C, regardless of the altitude of occurrence.

Other theories.- F. H. Ludlam (reference 38) calculates the conditions of growth of a hailstone by the process of accretion on the basis of its heat budget. The coagulation process gives the growing ice particle a coat of supercooled water which commences to freeze at the ice surface. A rise of temperature occurs as the latent heat of fusion is liberated, and the temperature at the ice surface and within the liquid film tends to rise to 0° C. This particle, however, loses heat to the environment both by conduction and evaporation; the rate of growth is then dependent upon the rate at which this heat loss can proceed. According to Ludlam, this explanation is also true for larger ice particles even at temperatures as low as -20° or -30° C. The presence of alternate layers of clear and opaque ice in the hailstone is considered to be the result of successive passages of the hailstone through critical conditions caused by changes in radius, falling speed, temperature, pressure, and liquid water content in the cloud.

Dr. E. J. Workman (reference 39) has for a number of years been investigating thunderstorm electrification. Although no theory on the formation of hail is made by Dr. Workman, he associates the formation of hail with the lightning phenomenon. During laboratory experiments, it was determined that a charge is generated as water, which contains a slight amount of contaminants, freezes. The sign and magnitude of this charge is determined by the nature and amount of contaminant present. This electrical effect occurs only during the freezing process. Applying these experiments to thunderstorms, Dr. Workman theorizes that the electricity of the thunderstorm is generated during the formation of hailstones. Assumption of this mechanism for the production of thunderstorm electricity suggests possibilities for the control of lightning discharges.

Concluding remarks.- From the foregoing description of hail-formation theories, it can be seen that most of the theories start with certain basic assumptions and then are developed with emphasis on a particular phase of the hail-formation process. Points of similarity include (1) vertical currents, (2) temperature variations, (3) hailstone layer formation, and (4) time or path length requirements. Although Schumann, Gaviola, and Alsina Fuertes emphasize hail formation on descent only, they do not deny that hail may also form in ascending currents and consider that small upward currents retard the fall of the stone. Although Horton described in detail the vortex-ring type of hailstorm, which includes both ascending and descending currents, he also believes that the tubular-convection type of hailstorm occurs by the ascending-current method presented by Humphreys. Gaviola, Alsina Fuertes, Ludlam, and Weickmann show much similarity on the formation of opaque and clear ice layers.

SURVEY OF HAIL PHENOMENON WITH RESPECT TO AIRCRAFT OPERATION

With the growth of aviation, the problems that have arisen from aircraft encountering hail during routine flights have become more and more significant. These hail encounters can cause severe damage to aircraft, in some cases as high as $25,000 per encounter. Nearly all external components of the aircraft, especially the nose section and the leading edges of the wing and tail, are subject to damage. In the early days of aviation, instrument flying was not a common practice; however, now that more and better instruments are installed in aircraft, pilots are not averse to fly for an appreciable time through cloud formations and to land with weather conditions below contact minimums. As a result, aircraft are encountering more frequently thunderstorms in which hail falls. This section deals with the resultant hail damage to aircraft and possible means of eliminating such damage.

EXTENT OF HAIL DAMAGE TO AIRPLANES

The search for information on hail damage to airplanes has revealed that very few articles have been published on the subject, but that appreciable information is scattered among the operational, maintenance, and safety records of the airlines, the U.S. Air Force, and other agencies. Data on 47 cases of hail damage to airplanes are presented as tables II to V. In some of these cases only a small amount of information is available. Table II(a) includes eight cases of hail damage to larger-transport airplanes; table II(b) gives seven cases of damage to smaller-transport airplanes; and table III lists seven cases of hail damage to military airplanes. Limited case histories are given for cases 23 to 47 in tables IV and V. Table IV gives 16 cases of hail damage to transports, whereas table V includes seven cases of damage to military airplanes and two sample cases of damage to airplanes on the ground. All 47 cases presented in tables II to V occurred in the United States except one, which occurred just over the Mexican border. After the analyses of the 47 cases were completed, 31 additional cases became available and have been included herein (table VI) as supplementary information only.

From the photographs available on airplane damage caused by hail, a series of 27 photographs have been included in the present paper as figures 12 to 21. All of the pictures have been taken from the cases presented in the tables.

Wing and Tail Damage

The leading edges of the wing and the tail, as would be expected, were the most susceptible to damage. The amount of damage to leading edges that required extensive repair is shown in a subsequent section. The leading edges of thermally de-iced airplanes, because of the method of construction, are more susceptible to damage than are wings with more leading-edge stiffeners. Wing and tail leading-edge damage can be seen in figures 13(b), 13(c), 13(d), and 14(f). Figure 21 shows the damage sustained by an F-82 fighter-type airplane equipped with thermal de-icing. In addition to the leading edges, the control surfaces are frequently damaged, especially if the surfaces are fabric covered, as in the Douglas DC-3, Beech D18S, and others. Figure 16 illustrates damage to a fabric-covered wing surface of a DC-3.

Fuselage Damage

Damage to the fuselage is generally confined to the forward sections, that is, the nose and the cockpit areas. Windshields or canopies or both are sometimes broken or cracked to such an extent that pilots fear that normal cruising speeds would cause the broken pieces to be blown into the cockpit. With respect to the damage to windshields, the damage caused by hail may be amplified in airplanes with pressurized cockpits because of the added stress from internal pressure. Occasionally one side of the fuselage is damaged more than the other. This condition is presumably caused by the pilot skidding the airplane, thus exposing one side of the aircraft to the falling stones. Plexiglass nose coverings are affected in much the same manner as windshields. Fuselage damage is shown in figures 12(a), 13(a), 14(a), and 17(a); windshield damage, in figures 14(c) and 17(b).

Engine and Propeller Damage

Engine cowlings are damaged to about the same extent as leading edges. Ignition harnesses on engines are frequently damaged sufficiently to require replacement. Cooling fins also are very susceptible to damage. (The only instance of engine failure during an encounter with hail was reported in a Lockheed Constellation which experienced a simultaneous failure of all four engines; this failure was probably due to blocking of the air intakes by hailstones. The engines were restarted after the airplane had left the hail and turbulence area.) Propellers and propeller assemblies are damaged to some extent, but again the damage reported has never been extensive enough to be serious. Types of damage to engines and propellers can be noted in figures 14(b), 18(d) and 20(d).

Accessory Damage

Turrets, radar coverings, antenna loop housings, and landing and navigational lights are the chief accessories that are subject to damage. Landing lights that are imbedded in the leading edge of the wing are, for obvious reasons, more susceptible to damage than are the retractible type. Accessory damage is shown in figure 14(d).

CORRELATION OF HAILSTONE SIZE WITH AIRPLANE DAMAGE

In order to determine the extent of damage caused by various-size hailstones at varying impact velocities, the Indianapolis Experimental Station of the CAA conducted tests on the metal portions of typical Douglas DC-6 and DC-3 wing sections (references 40 and 41). Ice spheres, frozen in appropriate molds, were made in sizes of 0.75, 1.25, and 1.88 inches in diameter (weighing approximately 0.1, 0.5, and 1.6 oz, respectively) and were fired by a compressed-air gun at the wing sections at speeds ranging from 110 to 460 miles per hour. The resulting damage and amount of indentation are shown photographically in figures 22 and 23 and, graphically in figure 24.

The following facts and inferences may be drawn from the CAA tests:

(1) The extent of damage varies with the mass of the hailstone, the impact velocity, the impact angle, and the type (thickness, strength, and shape) of the material hit by the hail.

(2) Hailstones less than 0.75 inch in diameter do not cause significant damage at airplane speeds between 200 and 300 miles per hour.

(3) Leading-edge dents sufficiently large to require repair, say 0.1-inch deep, were produced on a DC-6 wing section (0.040-inch 75S-T aluminum) by

(a) A 0.75-inch ice sphere at 420 miles per hour
(b) A 1.25-inch ice sphere at 300 miles per hour
(c) A 1.88-inch ice sphere at 210 miles per hour

A DC-3 wing section (0.045-inch 24S-T aluminum) was damaged to the same extent by ice spheres of the same three sizes at speeds of 300, 180, and 120 miles per hour, respectively.

(4) Two-inch hailstones cause extensive damage to airplanes at speeds above 300 miles per hour. At 378 miles per hour, a 1.88-inch ice sphere caused the surface of a 75S-T aluminum skin to stave in over an appreciable area; at 294 miles per hour it had the same effect on 24S-T aluminum skin.

It is not immediately evident how the results of the CAA tests can be extrapolated to situations not specifically covered by the tests; however, an analysis can be made as follows to determine approximately how the depth of dent depends upon impact velocity, skin thickness, and type of material. It is assumed that the impact is normal to the skin, that a small flat circular portion of skin is affected by the hailstone, that the deformation of this portion is conical, that the deformation is resisted entirely by the membrane stress produced by the stretching of the skin, that the stretching of the skin is a purely plastic and irreversible action (the radical membrane stress has, at all times, a constant value equal to the yield stress of the material), that the depth of the dent is small compared with the radius of the affected portion of skin, and, finally, that all the kinetic energy of the ice sphere is absorbed in straining the skin.

On the basis of the foregoing assumptions, the force F necessary to produce a deflection d beneath the force is given by

$$F = (2\pi r)\left(\sigma_y t\right)\frac{d}{r} = 2\pi\sigma_y td$$

where r is the radius of the circular portion of skin affected, σ_y is the yield stress of the material, and t is the skin thickness. The strain energy absorbed by the aluminum skin with a deflection d is equal to the external work done upon it, or

$$\text{Strain energy} = \frac{1}{2}\,Fd = \pi\sigma_y td^2$$

The kinetic energy of the hailstone prior to impact is given by

$$\text{Kinetic energy} = \frac{1}{2}\,MV^2$$

where M is the mass of the hailstone and V is the impact velocity. Equating kinetic energy to strain energy and solving for d gives the following expression for the depth of the dent:

$$d = \frac{V\sqrt{M}}{\sqrt{2\pi\sigma_y t}}$$

This result may also be written as

$$d = k \frac{V\sqrt{W}}{\sqrt{\sigma_y t}}$$

where W is the weight of the hailstone and k is a proportionality constant. The theoretical value of k is 0.00053 when V is measured in miles per hour, W, in grams, σ_y, in kips per square inch, and t and d, in inches.

Because of the many assumptions made in the theoretical analysis, it would be better to adjust the value of k empirically to account for additional factors which were eliminated in the original assumptions. Known combinations of values of d, V, W, σ_y, and t from the CAA tests were therefore substituted in the formula and an experimental value of k was calculated. The resulting values were not constant but varied as shown in the following table:

d/t	k
5	Between 0.0002 and 0.0004
15	Between 0.0005 and 0.0007
25	Between 0.0008 and 0.0010
35	Between 0.0010 and 0.0012

ESTIMATION OF HAILSTONE SIZE FROM AIRPLANE DAMAGE

By analyzing 52 photographs covering 11 cases of actual hail damage to airplanes, the authors of the present paper attempted to estimate the sizes of hailstones encountered by these damaged airplanes. Since photographs are generally taken of only the more seriously damaged aircraft, it is logical to assume that the hailstones causing the damage shown in these photographs are among the largest encountered by aircraft. These photographs are, therefore, a record of extreme cases rather than of average cases.

In order to estimate the sizes of the hailstones which caused the airplane damage in the 11 cases, the last formula of the previous section, solved for W, was used in conjunction with the previous table. The depth d of the largest single isolated dent on each damaged part was estimated from the photographs by several qualified aircraft inspectors (isolated dents were used in order to eliminate the effects

of cumulative damage by numerious hits in the same place); the yield stress σ_y and the skin thickness t were obtained from the maintenance manuals on the particular type of airplane; and the impact velocity V was taken to be the true airspeed of the airplane at the time of encounter. A specific gravity of 0.7 was assumed in converting W to the size (diam.) of the hailstone.

The results of the calculations of maximum hailstone size are shown in the next to last column of the following table. Because of the variation in the depths of the dents over various components of the airplane constructed of the same type of aluminum alloy and the lack of preciseness in the factor k, the most probable single value of the estimated hailstone size is given, together with an indication of the range of possible error for each case. Since the kinetic energy of a hailstone is probably the most significant index of its ability to inflict damage, the kinetic energy for each case (based on the most probable hailstone size) is given in the last column of the table for comparison purposes only.

Case	Photograph of damage (fig.)	Type of airplane	Estimated true airspeed (mph)	Maximum hailstone size (diam.) (in.)	Kinetic energy of impact (ft-lb)
1	12	DC-6	270	1.3 ± 0.2	75
[a]3	13	DC-6	295	1.4 ± 0.3	105
7	14	DC-6	360	1.5 ± 0.3	195
9	15	DC-4	185	1.7 ± 0.3	50
11	17	DC-3	225	1.5 ± 0.2	75
15	--	D18S	170	1.3 ± 0.2	30
16	18	B-29	200	1.8 ± 0.2	100
17	19	B-29	220	1.7 ± 0.2	100
19	20	B-29	265	1.4 ± 0.2	85
20	--	A-26	270	1.5 ± 0.2	120
22	21	F-82	305	1.6 ± 0.2	165

[a]Reference 42 states that circular templets were fitted into the dents caused by the hail, and it was found that the size of the hail was predominantly $1\frac{3}{8}$ inches in diameter. This figure compares favorably with the calculated size of 1.4 inches.

On the basis of the evidence shown in this table, the largest hailstones likely to be encountered in flight appear to be about 2 inches in diameter.

ANALYSIS OF FLIGHT AND WEATHER CONDITIONS ASSOCIATED WITH ENCOUNTERED HAILSTORMS

Geographical Distribution and Time of Occurrence

The geographical locations of 57 airplanes at the time they encountered damaging hailstorms during cross-country flights over the United States are presented in figure 25(a). These accidents, for which more complete information is given in tables II to IV, were used to analyze the geographical distribution of hail encounters. (Additional cases became available after the analysis was completed and are included in figure 25(b).) Figure 25(a) includes 10 cases, not given in the tables, in which only a location is known. Inquiries concerning the occurrence of damaging hail over the North Atlantic and North Pacific Oceans adjacent to the United States did not reveal any cases of significant aircraft damage. Figure 25(a) shows the following distribution of hail encounters:

(1) Seventy-five percent of the cases occurred between the Mississippi River and the Continental Divide (shaded area)

(2) Only one case occurred west of the Continental Divide

(3) Only one case occurred east of the Mississippi River where the ground contour is under 500 feet.

Since a large percentage of the cases involve airplanes on transcontinental airways, and since the dense air traffic starts at New York and fans out along four transcontinental routes to the Pacific Coast with varying traffic volume, the figure does not give a true picture of the geographical distribution of hail aloft, especially east of the Mississippi River. The figure, however, does give a realistic picture of the risk of aircraft exposure to damaging hail and, from a consideration of the limited number of cases, favorable comparison is observed with the average annual number of days with hail (fig. 3(b)) and the crop-hail insurance rates (fig. 4). For ease of comparison, the locations of the 57 cases have been superimposed on these charts (figs. 3(b) and 4) and are shown as figures 26(a) and 26(b), respectively.

The region of maximum hail occurrence, indicated by all three distribution methods, is located between the Mississippi River and the Continental Divide and extends from Montana and North Dakota to New Mexico and Texas. An examination of the charts shows that the greatest hail frequency on the ground is in the western half of this region. It was therefore decided to divide the region arbitrarily into two approximately equal areas along the 2000-foot ground contour. Although the limited number of hail encounters is about evenly divided within these areas, the risk of encountering hail west of the 2000-foot contour should be greater because of the smaller volume of air traffic west of this contour. Figure 26(b) shows a marked increase in crop-hail insurance

rates west of the 2000-foot contour. The increase in hail frequency in this area may be partly explained by the increased upslope flow of east winds which result in the overriding of warm moist air over the north-south stationary front that often extends along the east slope during the spring and the summer months.

The monthly distribution of hail damage to 47 airplanes is shown in figure 27 and indicates that: (1) Out of 47 cases, 30 (64 percent) of the hail accidents, occurred during April, May, and June; and (2) May was the month of maximum occurrence, with 12 cases or 26 percent of the hail accidents. In the region between the Mississippi River and the 2000-foot contour, the maximum number of hail cases occurred during April and rapidly diminished to none by July. In the region between the 2000-foot contour and the Continental Divide, the maximum number of hail encounters occurred during May and gradually diminished to none by November (fig. 27).

The hourly distribution of hail damage to 34 airplanes is shown in figure 28. This figure indicates that: (1) Out of 34 cases, 19 (56 percent) occurred between 1400 and 1800 LST; and (2) out of 34 cases, 29 (85 percent) occurred between 1400 and 2200 LST. These results compare favorably with Lemons' hourly distribution of hailstorms presented in figure 5 which shows 52 percent occurring between 1400 and 1800 LST and 80 percent occurring between 1400 and 2200 LST.

The available data showed no correlation between the hourly distribution and the monthly distribution. In the small number of cases available (only 34), there appears to be no significant difference in the hourly distribution between geographical regions.

Thunderstorms Associated with Hail Encountered in Flight

Further studies were conducted to ascertain the weather factors associated with hail encountered by airplanes. The thunderstorms associated with these encounters were classified as to type: cold front, warm front, or air mass. Of 47 cases, 28 (59 percent) could be attributed to cold-front action, whereas 13 (28 percent) were caused by air-mass activity alone; the remaining 6 cases (13 percent) were caused by warm-front action. (Since more than half of the hail cases were caused by cold-front action, pilots should be more cautious than usual when flying in or near cold-front thunderstorms, especially during the spring and summer months.) The percentage of hail cases attributed to cold fronts is even more pronounced east of Indiana, where 8 of the 10 hail cases were from cold-front activity (fig. 25). It was also found that the cold-front storms occurred most frequently between 1400 and 2200 LST and reached a maximum at 1600 to 1700 LST. Most of the air-mass storms occurred at 1400 to 1500 LST and were practically negligible at other times.

Air-mass instability and the height of the freezing level were investigated to determine whether these factors could be correlated with hailstorm activity. Synoptic weather maps and upper-air soundings of the day of the hail encounter were examined, but no significant correlations could be found. The columns in tables II and III entitled "General weather situation" and "Estimated freezing level" are included for completeness of the case histories and for possible use in future research studies.

In-Flight Weather Observations When Hail Was Encountered

In the great majority of the accidents caused by hail, thunderstorms were visible in the vicinity. Occasionally, hail was encountered outside but near a thunderstorm. This hail was presumed to have blown out of the anvil of a cloud. In every case in which a thunderstorm was not mentioned specifically in the report of the encounter, indications were that a thunderstorm was present. In cases 1 to 22, (tables II and III) it will be noted that, in all but two instances, turbulence, drafts, lightning, and/or radio static were observed. Of the two cases where none of these phenomena was mentioned, one was an encounter with hail in the clear and the other was not fully reported - the airplane ran into hail shortly after take-off while flying through rain but apparently not through clouds. The onset of hail and turbulence or drafts was almost simultaneous in several cases.

IN-FLIGHT AVOIDANCE BY RADAR DETECTION

Many military airplanes are now equipped with radar which can be used to detect areas of precipitation. By using this equipment, the pilot can avoid the precipitation area; but if it is necessary to fly through the precipitation, which may extend over a large area, the pilot is unable to pick the safest route, as the radar gives no indication of the type or intensity of precipitation. Military and civilian air-transport operators have therefore become interested in determining the practicability of air-borne radar which enables the pilot to avoid the dangerous areas within thunderstorms and squall lines and to fly through precipitation clouds with safety and comfort.

American Airlines, Inc. (reference 43) investigated the use of radar for in-flight avoidance of severe turbulence and heavy precipitation (including hail) in thunderstorms and squall lines. The flight tests made with specially built radar equipment gave no conclusive results on hail avoidance; however, the tests indicated that future research in this direction could lead to the avoidance of damaging hail.

On the assumption that good correlation existed between rate of change of rainfall rate (rainfall gradient) and maximum turbulence, a modern 3-centimeter radar set was modified for this investigation so that the PPI scope would indicate the rainfall gradient. Since the strength of the radar echo depends upon the number and the size of the precipitation particles and the path length in the cloud, the variation in the strength of the return signal is a function of the precipitation. The echo on the PPI scope of this modified radar set has the usual appearance except that the center section of the echo is erased when the rate of precipitation is above a predetermined amount. The spacing between the no-echo area and the erased-echo area gives a measure of rainfall gradient.

During the flight tests the airplane flew a total of 600 miles through, or immediately adjacent to, 40 thunderstorms. Hail, graupel, or snow pellets (soft hail) were collected by a hail catcher (fig. 29) 32 times during these flights. A typical example of the small hail and graupel caught in the hail catcher during flights through thunderstorms at a temperature just above freezing (4° C) is shown in figure 30; a typical example of snow particles and soft hail caught at a temperature just below freezing (0 to -5° C) is illustrated in figure 31 (reference 44). Difficulty was encountered in catching hailstones at cloud temperatures just below freezing because soft hail, slush, and snow particles were also present and caused the surface of the hail catcher to become coated with ice.

When the 32 hail encounters during these test flights were analyzed, it was found that 31 cases occurred in the heavy-rain area and only 1 case occurred in the light-rain area. The PPI scope indicated that, of the 31 encounters which occurred in heavy rain, 28 cases (90 percent) occurred during the first 15 seconds (distance, 1 mile) of heavy rain following the light rain. In no instance, however, were hailstones encountered larger than 3/4 inch in diameter. From the limited data available, hail appears to be generally located in the heavy-rain area and close to the outer periphery of that area.

CORRELATION OF AVAILABLE INFORMATION ON HAIL

Previous sections have presented the information available from literature on the hail phenomenon and a survey of hail as it affects aircraft operations. Although the material in these sections has been presented independently, it is closely associated. In addition, the material in each of the previous sections suggests ways to avoid or to reduce hail damage to aircraft. This section, therefore, correlates the hail information previously discussed and serves as a guide in the avoidance or reduction of hail damage.

GENERAL FEATURES

Small solid particles (called small hail) apparently form in every thunderstorm and melt before falling to the ground. In the more violent thunderstorms, however, these initial solid particles continue to enlarge into hailstones by the sublimation and condensation processes, and a certain size appears to predominate in each storm. Hail occurs in narrow bands during the mature stage (or late in the growing stage) of the thunderstorm cycle and is closely associated with the heavy-rain area.

Hail is usually composed of alternating layers of clear and opaque ice and has an average specific gravity of 0.7. The shape of most hailstones is spherical, although conical and discoidal stones frequently form. The size of hail aloft may vary from its size on the ground, as the stone may continue to grow during its final descent to the earth, or may melt partially after it falls into regions of above-freezing temperatures. Although the largest hailstone authentically recorded in the United States measured 5.4 inches in diameter and weighed 1.5 pounds, the average size of hail reported on the ground is about 0.6 inch in diameter and its weight, 0.05 ounce. The average size of hail aloft is unknown; however, calculations made from the extent of hail-damaged airplanes indicate that the size of hailstones encountered aloft ranges up to about 2 inches in diameter and the weight up to 1.8 ounces. A United Air Lines study showed that, in the area between Chicago and Denver, hailstones larger than 1 inch occur in about 1 out of 800 thunderstorms, whereas hailstones larger than 2 inches occur in about 1 out of 1600 thunderstorms.

Although hail is associated with thunderstorms, the geographical distributions of the two are not the same. Hail occurs with greater frequency in the continental interiors of the middle latitudes, diminishing in frequency seaward, equatorward, and poleward. The distribution and

occurrence of hail-producing thunderstorms which cause airplane damage over the United States are outlined as follows:

(1) Seventy-five percent of the damaging hail encountered by airplanes occurs between the Mississippi River and the Continental Divide. This distribution agrees with ground weather reports and crop-hail insurance rates as shown in figure 26.

(2) Sixty-four percent of the hail which causes airplane damage occurs during April, May, and June. This period compares favorably with the months of maximum hailstorms reported on the ground as April, May, and June (fig. 6(a)).

(3) Fifty-six percent of the hailstorms encountered aloft occur between 1400 and 1800 LST, whereas, 85 percent occur between 1400 and 2200 LST. These percentages are in close agreement with ground reports of 52 and 80 percent, respectively (fig. 5).

(4) Fifty-eight percent of the damaging hail encountered by airplanes is caused by cold-front thunderstorms, whereas, 28 percent is caused by air-mass thunderstorms. The cold-front storms occur most frequently between 1400 and 2200 LST; most of the air-mass storms occur at 1400 to 1500 LST and are practically negligible at other times.

(5) Pilot reports indicate that the horizontal distance flown in hail averages 5 miles but ranges from 1 to 30 miles. Surface data show that the most common width of the hailstorms is 1 to 2 miles but widths ranging from a few yards to 75 miles have been reported.

(6) The Thunderstorm Project showed that hail was seldom found at more than one or two levels in the same storm and that it occurred most frequently at an altitude between the freezing level and 20,000 feet.

AIRPLANE OPERATION AND HAIL

Although no fatal airplane accident is known to have been caused solely by hail, this phenomenon has caused severe damage to airplanes, in some cases as high as $25,000 per encounter. The nose section and the leading edges of the wing and tail are subject to severe damage, and windshields have been broken or cracked to such an extent that pilots feared that normal cruising speeds of the airplanes would cause the broken pieces to be blown into their eyes. The extent of damage varies with the mass of the hailstone, the impact velocity, and the type of material hit by the hail. Hailstones less than 0.75 inch in diameter do not cause significant damage at aircraft speeds between 200 and 300 miles per hour. Calculations from photographs of hail-damaged

airplanes indicate that the largest hailstones likely to be encountered in flight are about 2 inches in diameter.

From the analysis of flight and weather conditions associated with hailstorms, it is evident that, until radar or other hail-detection equipment becomes available, successful hail avoidance is directly dependent upon pilot judgment. In order to exercise good judgment, the pilot should (1) be familiar with the occurrence of hail and the effect of hail on aircraft, (2) know the over-all weather conditions before take-off, (3) obtain the latest in-flight weather advisories, and (4) be aware of potential developments so that he can recognize and evaluate them as they occur. If a pilot has a general understanding of when and where hail forms and the weather conditions associated with hailstorms, he knows when he should discuss hail during preflight weather briefing with the forecaster and when he should require additional pertinent weather information during flight. Unexpected hail encounters could thus be reduced.

If the location and time of the flight coincide with possible hailstorm conditions, visual pilot observation should be made (if possible) of all thunderstorm clouds that are in line with or directly adjacent to the flight path of the aircraft. Since the degree of severity of a thunderstorm can be associated with the stage of its life cycle, and since hail usually occurs during the mature stage, greater caution should be taken by the pilot when is is flying near or through this stage of the storm. A mature storm can be described as having a sharp-edged cauliflower appearance, and usually sharp cloud-to-ground lightning. A dissipating storm can be identified by its wispy-edged appearance and cloud-to-cloud, flickering-type lightning. The disadvantage of decreased visibility during night operations is partially overcome by the facts that only 25 percent of the hailstorms occur during the hours of darkness and that lightning is more readily visible at night.

Many military and commerical pilots make use of visual soft spots in navigating through cumulo-nimbus clouds. A so-called visual soft spot, however, is not always a reliable means of determining the best path through a thunderstorm, because hail has been occasionally reported in the clear air outside thunderstorm clouds. As a result of recent experiences of this nature, at least one airline advises pilots to stay away from the edges of cumulo-nimbus clouds when the temperatures at flight altitudes are below freezing. It should also be remembered that, although hail may not be encountered by aircraft passing through a thunderstorm, damaging hail may be encountered in another storm within the same general area or at a different altitude in the same storm.

After the airplane enters a thunderstorm and encounters hail, the pilot must decide whether he should turn to get out of the hail area or continue through the hail area on his original heading. It appears

that, after hail is encountered, the type of evasive action to be taken depends again on pilot judgment and the decision should be based on all known factors regarding the position of the airplane with respect to the storm. If the flight path is parallel to the edge of the storm, a turn is obviously the best solution. If the relative position of the storm is unknown, the best course is to continue through the storm. This course is especially advisable when instrument flight conditions, poor radio reception, and other adverse factors are involved. The speed of the airplane, however, has a profound effect on the amount of damage sustained and should be reduced as soon as possible.

Hail damage may be reduced in future aircraft operations by the elimination of destructive hail or by aircraft avoidance of hailstorms by means of radar detection. Attempts have been made to eliminate destructive hail by seeding potential hailstorms, and the Rogue River Valley Hail Prevention Project has been successful in eliminating hail over a limited area in Oregon. American Airlines, Inc. has experimented with a modified radar set which detects the rainfall gradient (the rate of change of rainfall rate with distance), a parameter which may have good correlation with turbulence and hail. Although some accepted conclusions have been reached with respect to turbulence, no definite conclusions can as yet be drawn concerning hail.

FORECASTING HAIL

The meteorologist can be of great assistance in minimizing the hail hazard to airplanes by placing increased importance on forecasting damaging hail and potential hail-producing thunderstorms. Since most hail exists in narrow bands within thunderstorm clouds that are in the late building or early mature stage, the meteorologist must first analyze all available information which can be used to forecast thunderstorms. At present two methods are used to forecast thunderstorms - the parcel method and the slice method; both require data from upper-air soundings. The parcel method is in more common use today, as it is simpler to use and sufficient with our present knowledge. The slice method is much more complicated, but if properly applied it should give more accurate results. One representation which makes use of the parcel method is the Theta-E map. This map shows the fields of equivalent potential temperature and of moisture content, both drawn for a selected level (generally 700 millibars).

If thunderstorms are assured, the meteorologist can turn his attention to a forecast of possible hail. No specific rules can be given for forecasting hail, as associated weather conditions appear to vary with the locality; however, it is well understood that the lapse rate, moisture content, and lifting forces are important factors involved in forecasting the severity of thunderstorms and the possibility of hail. A

United Air Lines study (reference 8) revealed that the frequency of thunderstorms producing large hail (1-inch in diameter or larger) is 1 in 400 when the lapse rate, as indicated by the nearest sounding, is greater than 2.5° C per 1000 feet. The frequency is only 1 in 1200 when the lapse rate is smaller than 2.5° C per 1000 feet. Large hail appears more frequently when the base of this unstable region is below 7000 feet. In addition, the moisture content of the air should be above 70 percent relative humidity for a depth of 15,000 feet, and this moist layer should straddle the freezing level.

A certain amount of lifting is required to instigate vertical convective currents which are necessary for the development of hail-producing thunderstorms, and, therefore, the thermal, orographic, and frontal lifting forces should be given careful consideration. Air-mass hailstorms can be produced from a large amount of thermal lifting force alone, but the geographical distribution and time of occurrence of air-mass hailstorms indicate that, in the majority of cases, both orographic and thermal lifting forces may be required. As the greatest number of frontal hailstorms occur in the late afternoon, it also appears that both frontal and thermal lifting forces usually are necessary for frontal hailstorms. Since cold fronts produce the majority of hailstorms which result in airplane damage, the meteorologist should be extremely careful in locating all fronts on the synoptic weather map and in detecting the first signs of the development of prefrontal squall lines. Some cold fronts and prefrontal squall lines are very weak at night, but with added solar heating during the day they intensify and produce the lifting forces required for severe thunderstorms and hailstorms.

A certain amount of judgment on the part of the meteorologist must be used in forecasting hail. Local forecasting experience gained by a meteorologist who is stationed at one locality for a long period of time is probably the most significant factor which contributes to the accuracy of his hail forecasts. By analyzing the climatological records of the forecast area, a meteorologist in a new location can obtain valuable information on the types of synoptic patterns and on the critical values of the upper-air elements which prevail when hailstorms occur. A typical analysis of the weather conditions associated with hailstorms has been made by United Air Lines for the Denver area (reference 16).

In general, the meteorologist is able to detect potentially dangerous hail situations when making an area or route forecast, and during preflight briefing he should warn the pilot of the possibility of hail when this condition exists. After take-off, efforts should be made to transmit hail information to the pilot when pilot in-flight weather reports and the latest surface observations indicate that hail exists but was not forecast for the area.

In summarizing the general requirements for the forecasting of severe thunderstorms and hailstorms, the following points should be kept in mind:

(1) Amount of moisture aloft: Although a sounding may show great degrees of instability, no clouds develop if the atmosphere is exceedingly dry. A layer should be considered moist if the relative humidity is above 70 percent. The moist layers should cluster about the freezing level.

(2) Height and thickness of the unstable layer: Cumulus clouds form with the instability entirely below the freezing level, but for the cumulus to reach severe thunderstorm proportions and cause hail the unstable layer should extend at least 15,000 feet above the cloud base.

(3) Height of the freezing level: Hail is more likely to form with a low freezing level (springtime conditions), since more of the unstable region is in temperatures below 0° C.

(4) Amount of thermal heating: For vertical convective currents to begin, a certain amount of surface heating is required. This amount can be determined by calculating the dry adiabatic temperature at the convective condensation level and estimating the expected maximum surface temperature.

(5) Amount of orographic or frontal lifting: Trajectory of the air over geographical or frontal slopes can be used to determine how much the air will be lifted. A layer already unstable will of course become more unstable upon lifting.

(6) Amount of local forecasting experience: By studying the climatological records of the particular area where hail forecasts are to be made, valuable information can be obtained on the type of synoptic patterns and on the critical values of the upper-air elements which prevail in the area during days when hailstorms occur.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., January 17, 1952

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TABLE I

FREQUENCY (N) AND PERCENTAGE DISTRIBUTIONS OF VARIOUS HAIL INTENSITIES AT GIVEN ATLITUDES

[From reference 19]

(a) Florida Thunderstorms (1946)

Hail intensity	Flight altitude, (ft MSL)									
	6,000		11,000		16,000		21,000		26,000	
	N	Percent	N	Percent	N	Percent	N	Percent	N	Percent
Light	0	0	1	1	4	3	1	1	2	3
Moderate	0	0	1	1	6	4	3	3	0	0
Heavy	0	0	1	1	3	3	0	0	0	0
No hail	96	100	128	97	115	90	111	96	79	97
Total	96	100	131	100	128	100	115	100	81	100

(b) Ohio Thunderstorms (1947)

Hail intensity	Flight altitude, (ft MSL)									
	5,000		10,000		15,000		20,000		25,000	
	N	Percent	N	Percent	N	Percent	N	Percent	N	Percent
Light	1	1	9	4	0	0	5	3	2	2
Moderate	0	0	2	1	2	1	3	2	0	0
Heavy	0	0	5	2	4	2	0	0	0	0
Unclassified	1	1	10	5	4	2	2	1	1	1
No hail	110	98	191	88	198	95	154	94	108	97
Total	112	100	217	100	208	100	164	100	111	100

TABLE II.- CASE HISTORIES OF HAIL DAMAGE TO TRANSPORT AIRPLANES

(a) Larger-transport airplanes

Case	Type of airplane	Date	Time	Location	Damage	Hailstone diam. calculated from pictures (in.)	Flight conditions: Estimated true airspeed in hail (mph)	Flight conditions: Altitude (ft MSL)	Flight conditions: Air temp. (° C)	Flight conditions: General flight direction	In-flight weather conditions before encounter
*1	Douglas DC-6	Sept. 14, 1947	1516 CST	NE. Mexico; 25 miles NW. of Monclova	Nose section, fuselage above windshield, cowling, leading edges of wing, and so forth	1.3 ± 0.2	270	18,000	0	NW.	VFR Clearance: Changed course twice to go around small but towering cumulus; large cumulo-nimbus directly ahead and to right having a top 10 miles in diameter at 30,000 ft and extending higher. Two small cumulus to left; tops 20 to 25,000 ft. Stratus overhanging deck at 20,000 ft. Went under stratus and just left of cumulo-nimbus. Encountered heavy rain and saw one flash lightning to right. No precipitation ahead or to left. Hail.
2	Douglas DC-6	April 27, 1948	1600 EST	**EC. Ohio; Zanesville	Leading edges of wing and tail, cowlings, and nose section	Unknown	245	18,000	-12	W.	IFR Clearance: Ran into squall line in eastern Ohio, slowed to 170 mph IAS. Smooth after first entering cloud, light hail after a few minutes; an updraft increased airspeed to 190 mph IAS, then moderate hail.
*3	Douglas DC-6	May 2, 1938	2030 EST	E. Tennessee; 30 miles N. of Knoxville	Nose section, fuselage and dome above windshield, wing tips, propellers, de-icer, cowling, air scoop, and oil cooler	1.4 ± 0.3	295	19,000	0	NE.	IFR Clearance: Tops of clouds 11,000 ft. Lightning visible to south of course. A front was moving across to the southeast. Through northern Tennessee, tops were 18,500 ft with some higher. Went through several tops with no turbulence; then into a top with heavy hail immediately after entry.
4	Douglas DC-6	May 25, 1948	1935 CST	SW. Texas; Midland	Windshield, nose cap battered, cowlings, and leading edges dented; repair cost $18,146	Unknown	270	16,000	5	W.	IFR Clearance: Encountered broken to scattered thunderstorms with slight wing icing, but no appreciable turbulence; then ran into hail. Outside temperature reported 5.5° C.
5	Douglas DC-6	June 25, 1948	2245 CST	**C. Oklahoma; 30 miles W. of Oklahoma City	Nose cap dented, paint off engine cowling, small dents in horizontal and vertical stabilizers	Unknown	170	16,000	Unknown	W.	IFR Clearance: A line of thunderstorms extended northeast-southwest on the take-off. Entered cloud after climbing 16,000 ft. Encountered hail immediately. Altitude limited to 16,000 ft because of engine trouble.
6	Douglas DC-6	March 30, 1949	2030 CST	**C. Illinois; Bloomington	Leading edges and nose dented	Unknown	170	7,000	4	NE.	IFR Clearance: Between layers at 7,000 ft to central Illinois. Went on instruments with light turbulence. After 10 min it became apparent they were nearing center of thunderstorm activity, with moderate to heavy rain and considerable lightning. Slowed to 160 mph IAS then through light hail.
*7	Douglas DC-6	May 25, 1949	2010 CST	SW. Texas; Guadelupe Pass	Nose, windshield, cowlings, and all leading edges; repair cost $25,165	1.5 ± 0.3	360	14,000	6	W.	IFR Clearance: A line of thunderstorms extended from eastern New Mexico south-southwestward into Mexico. Overcast at 20 to 25,000 ft. from thunderstorms eastward, joining thunderstorms at 20,000 ft. Tops of clouds to north estimated 40,000 ft. Hail was reported on ground with thunderstorms and dust to 13,000 ft. Slowed to 170 to 180 mph IAS to enter, anticipated light to moderate turbulence and rain; 2 min after entering cloud airspeed built up to 275 mph IAS; then ran into hail.
8	Lockheed Constellation	April 25, 1948	1730 CST	**C. Louisiana; Alexandria	Damage not mentioned. (Several passengers injured because of hitting the ceiling.)	Unknown	270	20,000	Unknown	SW.	IFR Clearance: On top of broken clouds at 10,000 ft, but through occasional light rain from a very high broken deck above. Air smooth, then a violent downdraft with light rain becoming very heavy rain. Quickly changed to updraft and heavy hail began.

*Pictures of hail damage in these cases are shown in figures 12 to 14.

**C refers to central.

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TABLE II.- CASE HISTORIES OF HAIL DAMAGE TO TRANSPORT AIRPLANES - Continued

(a) Larger-transport airplanes - Concluded

Case	Weather conditions during encounter			General weather situation	Estimated freezing level (ft)	Constructive remarks
	Hail with respect to cloud	Evasive action by pilot	Associated weather phenomena			
*1	Under overhang of a thunderstorm. Hail in very narrow band not restricting visibility. Hail, 15 sec in clear.	50° left turn and climbed.	No rain. One lightning flash. No turbulence.	Numerious air-mass thunderstorms. Little data available.	18,000 or lower	Unavoidable.
2	In thunderstorm. Hail 2 min.	None.	Light to moderate turbulence. Moderate updraft.	A north-south squall line and possible cold front through the area. Air mass was moist and unstable, very suitable for thunderstorms.	11,000	Hail was forecast. Impress pilots to use extreme care and minimum safe speed when hail is probable.
*3	In top of thunderstorm. Hail 2 to 3 min.	180° left turn.	Severe turbulence with hail. Poor radio reception.	Flight parallel and just ahead of northeast-southwest cold front. Air-mass information not available.	13,000	Caution pilots that if one thunderstorm does not have turbulence and hail this fact does not mean that all thunderstorms in the area do not.
4	Through thunderstorm. Hail 45 to 60 sec.	None.	Extreme turbulence for several minutes with the hail.	East-west cold front to south of the area. Thunderstorms more numerious to south of area. No reliable radiosonde available.	13,000	Meager information was available. Advise pilot to make complete post-flight report for future guidance of other personnel.
5	Into thunderstorm. Hail 10 min.	Descended to 12,000 ft.	Excessive St. Elmo's fire.	No fronts. Air mass moist and unstable, good for convectional thunderstorms.	14,000	Hail was forecast. Aircraft encountered hail at low airspeed, resulting in only minor hail damage. Impress pilots that if all equipment is not functioning properly, be extremely cautious.
6	Into thunderstorm. Heavy hail 15 sec. Light to moderate hail for 60 sec, estimated.	Slowed from 160 to 140 mph IAS.	Very heavy rain showers. Moderate turbulence. Appreciable lightning.	North-south cold front or occlusion passing area at time of accident. Air mass very moist and unstable with lifting.	9,500	Advise pilots to fly through thunderstorms at a rather high altitude rather than at a medium altitude. Warn pilots to keep airspeed low when there is any danger of hail.
*7	In cloud 2 min before hail was encountered. Hail 60 sec.	Immediate left turn.	Appreciable lightning. Moderate (not severe) turbulence.	Maps differ on synoptic situations. Cold front or squall line, oriented east-west, passed area at the time of the accident. Air mass would only produce thunderstorms with at least 3,000 ft lift.	14,000	Warn pilot that when hail is imminent to slow plane as much as possible. Caution pilots that visible "soft spots" in the thunderstorm area are often deceiving without the support of radar.
8	Report not clear. Hail less than 5 min.	None; because of engine stoppage.	Rain; severe turbulence; severe up and downdrafts.	Northeast-southwest squall line and cold front passing the area. Thunderstorms reported on ground almost everywhere.	13,000	Unavoidable.

*Pictures of hail damage in these cases are shown in figures 12 to 14.

TABLE II.- CASE HISTORIES OF HAIL DAMAGE TO TRANSPORT AIRPLANES - Continued

(b) Smaller-transport airplanes

Case	Type of airplane	Date	Time	Location	Damage	Hailstone diam. calculated from pictures (in.)	Flight conditions: Estimated true airspeed in hail (mph)	Flight conditions: Altitude (ft MSL)	Flight conditions: Air temp. (° C)	Flight conditions: General flight direction	In-flight weather conditions before encounter
*9	Douglas DC-4	Aug. 12, 1948	1545 EST	NW. Virginia; 40 miles NE. of Roanoke	Leading edges of wings, horizontal and vertical stabilizers, engine cowlings, both elevators, and nose section.	1.7 ± 0.3	185	8,000	10	SW.	IFR Clearance: Altitude 8,000 ft; circumnavigated few small thunderstorms; in and out of others; encountered rain and light hail for 1 to 2 min in these clouds; top possibly 15,000 ft; clouds all around. 40 min after take-off entered very light (light brown) clouds with anvil, at reduced speed; hail intensity increased.
10	Consolidated Vultee Liner	May 22, 1949	1545 EST	****C. West Virginia; 30 miles W. of Elkins	Dents in leading edges, some engine (propeller) trouble during hail.	Unknown	205	11,000	3	E.	IFR Clearance: Through central West Virginia; weather looked best to north and east. Flew around four large thunderstorms and picked a "soft spot" in the fifth; went between layers, light rain became moderate with some slush; then ran into hail.
*11	Douglas **DC-3	May 8, 1946	1655 MST	****NC. Colorado; 60 miles N. of Denver	Both wing tips, horizontal and vertical stabilizers, propellers, windshield, astrodome, ignition harness, cooling fins, and so forth.	1.5 ± 0.2	225	9,000	7	NE.	VFR Clearance: Long narrow belt of clouds just above flight level, estimated 1,2000 ft high; turned 15° left and descended 300 ft to go under clouds; updraft took plane from 8,300 to 10,000 ft into base of clouds; then downdraft and hail.
12	Douglas **DC-3	May 12, 1947	2045 CST	SE. Arkansas; 60 miles E. of Little Rock	Elevator ripped, windshield cracked, landing lights broken, and nose dented.	Unknown	160	2,500	20	SW.	VFR Clearance: Circumnavigated storms; under clouds; rain; night; lightning intense and blinding; then maybe into clouds; little hail and severe downdraft; 180° left turn; heavy hail during turn.
13	Douglas **DC-3	May 10, 1948	2015 MST	****EC. New Mexico; Clovis	Cowling dented, nose glass and landing lights broken.	Unknown	170	6,000	12	SW.	VFR Clearance, second part of trip: Night; under scud clouds with base 6,500 ft; lightning to right and left; encountered hail; scud clouds obscured thunderstorms.
*14	Douglas **DC-3	July 3, 1948	1830 EST	****C. Pennsylvania; 20 miles W. of Altoona	Elevator fabric.	Unknown	170	6,500	Unknown	E.	VFR Clearance: Changed to IFR when flight encountered haze and stratus clouds; vision impaired because of reflection of sun. Encountered hail and severe turbulence. Turned right to circumnavigate thunderstorm. Saw line of thunderstorms northwest to southeast.
15	Beech ***D18S	June 19, 1948	1700 EST	NE. West Virginia; Martinsburg	Horizontal and both vertical stabilizers, nose glass, and landing lights.	1.3 ± 0.2	170	7,000	Unknown	SE.	IFR Clearance: Encountered severe turbulence and little hail in one cloud; into clear with broken clouds underneath; went around next thunderstorm and 5 min later entered hole between 2 cloud sections of vertical development. Severe turbulence and hail; 180° left turn with violent updraft on right wing.

*Pictures of hail damage in these cases are shown in figures 15 to 17.

**For evaluation purposes the Douglas airplanes DC-3, C-47, and R4D are all classified as Douglas DC-3.

***For evaluation purposes the Beech airplanes D18S, JRB, and C-45 are all classified as Beech D18S.

****C refers to central.

TABLE II.- CASE HISTORIES OF HAIL DAMAGE TO TRANSPORT AIRPLANES - Concluded

(b) Smaller-transport airplanes - Concluded

Case	Weather conditions during encounter: Hail with respect to cloud	Weather conditions during encounter: Evasive action by pilot	Weather conditions during encounter: Associated weather phenomena	General weather situation	Estimated freezing level (ft)	Constructive remarks
*9	In thunderstorm. In cloud 10 min. In hail 8 min. Hail gradually increased becoming intense 3 to 5 min.	None.	Light to moderate turbulence (not severe).	Northeast-southwest weak cold front. Flight was made parallel to front and may have been in cold front. Numerous air-mass thunderstorms ahead of front.	13,500	Impress forecasters that positions of fronts and possibility of hail should be considered and included in forecasts to pilots. Caution pilots to select a route perpendicular to active cold front. Warn pilots to report by radio all unusual weather encountered to help forecasters and other pilots.
10	Between cloud layers. Hail 90 sec.	180° turn. (30° bank.)	Rain. Appreciable lightning. No radio reception.	Frontal situation not clear. Apparently flew through a north-south cold front. Radiosondes not available. Thunderstorms were forecast for southeastern Ohio.	12,000	Caution pilots that "soft spots" are not always "soft" when radar is not available.
*11	Just in or under cloud base. In hail 40 sec. Hail size $1\frac{1}{2}$ to 2 in. in diameter. Noise terrific.	Straight ahead; leveled off from downdraft at 7,000 ft MSL.	No rain. Light turbulence. Severe drafts - downdraft 1000 ft per min.	Air mass moist and unstable. Frontal situation is not clear. By using 24-hour maps (surface and 700 mb.), it is evident a cold front passed this area, but it cannot be picked out plainly.	10,000	Impress forecasters to watch indefinite fronts and keep associated thunderstorm activity in mind. Caution pilots not to fly under the hood while in marginal VFR weather.
12	In edge of thunderstorm. In hail 2 min.	180° left turn out of hail and cloud in 2 min.	Rain. No turbulence. Severe downdraft. Extensive lightning. Heavy static at low frequency.	Northeast-southwest upper cold front probably passed area at the time of the accident. All radiosonde in this area indicated thunderstorms were likely.	12,000	Weather was worse than forecast. Caution pilots that night flying through intense thunderstorms is dangerous. Warn pilots to change from VFR to IFR before IFR weather is flown into. Warn pilots to check range weather reports during adverse weather conditions.
13	Under cloud. In hail 30 sec, estimated.	180° turn.	Lightning to right and left. Light turbulence.	North-south cold frontal activity in the area. Air mass good for thunderstorms (unstable and moist).	11,000	Caution pilots that night flights are dangerous in thunderstorm area, especially when surrounding cloud decks obscure vision.
*14	In stratus cloud and into edge of thunderstorm. In hail short time.	Made small turn and climbed into light area 30° right turn then 100° right turn.	Light rain. Severe turbulence. Severe radio static.	Northwest-southeast weak surface warm front in vicinity. Probably air-mass thunderstorms also. No radiosonde available.	14,000	Remind forecasters to give pilots all weather information, including fronts en route. Advise pilots that it is safer in thunderstorm areas to fly on top of the stratus cloud deck where cumulus can be seen and not through stratus decks where visibility is limited.
15	In edge of thunderstorm. Hole closed between clouds. Hail 2 min, estimated.	180° left turn. Put inverted airplane under control. Let down in hole.	Severe turbulence. Severe radio static. Violent updraft at 4,000 per min	Northeast-southwest cold front in the area moving east. Air-mass data not available.	13,000	First hail encountered showed intensity of thunderstorm. Ground observers reported many storms in this area that day. Impress pilots of nature of storm activities and consequences, especially in thunderstorm areas. Warn forecasters that hail should be considered when briefing pilots.

*Pictures of hail damage in these cases are shown in figures 15 to 17.

TABLE III.- CASE HISTORIES OF HAIL DAMAGE TO MILITARY AIRPLANES

Case	Type of airplane	Date	Time	Location	Damage	Hailstone diam. calculated from pictures (in.)	Flight conditions				In-flight weather conditions before encounter
							Estimated true airspeed in hail (mph)	Altitude (ft MSL)	Air temp. (° C)	General flight direction	
*16	Boeing B-29	Oct. 31, 1947	0100 CST	**EC. Texas; 40 miles E. of Dallas	All leading edges of wings, horizontal and vertical stabilizers, all engine cowlings, propeller cuffs, cooling fins, cylinders; nose glass cracked.	1.8 ± 0.2	200	14,000 ±2,000	-3	ENE.	IFR Clearance: Night; radar inoperative; front sighted; VFR - flew parallel to line of thunderstorms, then through clear hole between two thunderstorms on left. Encountered severe turbulence and hail, turned 40° right, out of hail.
*17	Boeing B-29	June 3, 1948	1345 MST	**SC. Montana; 30 miles SE. of Billings	Leading edges of wings, horizontal stabilizers, engine cowlings, and cooling fins.	1.7 ± 0.2	220	10,000	6	NW.	IFR Clearance: Radar inoperative; could see scattered showers and various cloud formations. Pilot under hood. Went east of route to miss one storm. Entered shelf of clouds for a short time (5 min) and encountered rain, severe turbulence and hail; then into clear. Received radio report by another pilot - severe storm and tornado west of Billings - route was changed.
18	Boeing B-29	Aug. 1, 1948	1545 MST	**C. Wyoming; 40 miles NW. of Casper	Leading edges of both wings, horizontal and vertical stabilizers, engine cowling, ignition harness, navigation lights.	Unknown	250	20,000	-14	NW.	IFR Clearance: Radar inoperative; northeast-southwest squall line seen ahead at 16,000 ft. No breaks in squall line, so flew through. Entered cloud; then severe turbulence and rain; updraft took plane up 4,000 ft; 180° left turn; hail started in turn. Climbed to 28,000 ft; cloud tops 32,000 ft. Notified ATC to tell all pilots in vicinity.
*19	Boeing B-29	Aug. 11, 1948	1430 MST	SE. South Dakota; 15 miles SE. of Rapid City	Leading edge both wings, horizontal and vertical stabilizers, 28 engine cylinders, all ignition harness; propeller cuffs dented.	1.4 ± 0.2	265	9,000	10	NW.	IFR Clearance: Changed to VFR over destination. In radio contact with tower; letting down from 10,000 ft; circumnavigated small thunderstorm; hail at 9,000 MSL under edge of thunderstorm; visibility 15 mi. Made 90° left turn; notified control tower to warn other pilots in vicinity. Hail at airport; pilot was not warned by radio.
20	Douglas A-26	June 16, 1946	1845 CST	**NC Iowa; 120 miles NE. of Omaha	Horizontal and vertical stabilizers, air scoop, windshield, engine cowlings, gun mount covers.	1.5 ± 0.2	270	5,500	25 or less	SSW.	VFR Clearance: Flying under high broken clouds and beneath two cumulus (small thunderstorms). Possibly flew through thin white cloud at edge of cumulus base when hail was encountered. Copilot was in control and made post-flight report as the pilot was busy with the radio.
21	North American F-51	April 7, 1946	1500 CST	SW. Illinois; St. Louis	Both wing tips, horizontal and vertical stabilizers; propeller spinner dented.	Unknown	180	1,800	11	SW.	VFR Clearance: Still climbing after take-off; encountered hail under clouds in light rain.
*22	North American F-82	June 17, 1948	1700 CST	**WC. Nebraska; Alliance	Leading edge of wings, horizontal and vertical stabilizers; windshield broken; propeller spinners, air scoop.	1.6 ± 0.2	305	25,000	-28	SE.	IFR Clearance: IFR weather with occasional breaks overhead; while waiting for approval to let down under IFR, turbulence increased; windshield icing and lightning was observed; 30 sec in hail. Let-down approved. Flew into clear 20 sec after hail.

*Pictures of hail damage in these cases are shown in figures 18 to 21.

**C refers to central.

TABLE III.- CASE HISTORIES OF HAIL DAMAGE TO MILITARY AIRPLANES - Concluded

Case	Weather conditions during encounter			General weather situation	Estimated freezing level (ft)	Constructive remarks	Additional notes
	Hail with respect to cloud	Evasive action by pilot	Associated weather phenomena				
*16	Through edge of thunderstorm. In cloud 5 min. Hail 30 sec.	40° right turn.	Severe turbulence.	Northeast-southwest cold front passed area. Thunderstorms associated with cold front. Air mass unstable below freezing level, but dries out above.	12,000	Impress forecasters to use the slice method with frontal passage to improve thunderstorm forecasts. Caution pilots to keep aircraft radar in operation and use it before flying through frontal activity.	None
*17	In roll cloud and edge of thunderstorm. Hail started 4 min after entering cloud.	None.	Rain started upon entering cloud. Extreme turbulence with altitude variations of 400 ft.	Mostly air-mass thunderstorms. A cold front to the east could have enhanced activity. Air mass unstable enough to produce thunderstorms with good heating. Even more unstable to the south.	12,000	Caution forecasters to consider carefully thunderstorm forecasts. Impress pilots to listen to range weather reports. Advise pilots to report by radio all unusual weather encountered.	Hailstones the size of golf balls and stacked 12 in. deep were reported on ground at Red Lodge, Mont., at 1400 MST. Hail path 1/8 mile by 20 miles was reported at Columbus, Mont., between 1600 and 1630 MST.
18	Into edge of thunderstorm. In cloud and turbulence area for 5 min. Hail 60 sec. Hail size of golf ball. Noise terrific.	180° left turn. Flew long way to north to get around squall line.	Severe turbulence. Violent updraft from 16,000 to 20,000 ft.	No fronts. This air mass had been producing thunderstorms over the area for the past 4 days. Heavy thunderstorms should have been forecast by considering the radiosonde.	14,000	Advise pilots that in group flights aircraft with radar should lead group through intense thunderstorms. Forecast to pilot unknown.	None
*19	Under overhang of thunderstorm. Hail 20 sec. Hail on ground at airport.	90° left turn descending at destination.	None reported.	Seems to be air-mass thunderstorm, but flight was made parallel to east-west weak cold front farther to the east.	12,000	Radar availability and use unknown. Warn forecasters that hail should be considered when briefing pilots for flights through intense thunderstorm areas. Impress all personnel with the importance of immediate and accurate dissemination of unusual weather phenomena.	Both USWB and USAF take weather observations at Rapid City. USAF operates control tower. CAA operates radio range.
20	In edge of cumulus cloud. Hail 15 to 30 sec.	None.	No rain. No turbulence. Severe to moderate radio static.	Scattered thunderstorms caused by pre-cold frontal conditions. Air mass was such that heating alone should not produce thunderstorms. Hourly sequence did not report any rain or thunderstorms; only towering cumulus.	15,000	Advise pilots with no instrument rating to stay well clear of clouds. Warn pilots that clouds of vertical development and anvils can be obscured by surrounding cloud decks.	None
21	Under cloud base in light rain. Hail 15 sec.	None. Later skirted shower area.	Light rain.	East-west warm front to south moving north. Air mass through Missouri unstable with some dry layers; enough to set off thunderstorms with warm frontal lifting and heating.	12,000	Unavoidable.	None
*22	In cloud. Hail 30 sec. Left cloud 20 sec after hail stopped.	None. Received approval to let down.	Moderate turbulence. Windshield icing. Lightning.	Probably an east moving upper cold front was passing the area. Air-mass information not available.	14,500	Unavoidable by pilot. Appreciable hail was reported on ground in Wyoming and Kansas on this date. Impress ground personnel to transmit hail information to pilots and forecasters.	No hail was encountered by another aircraft flying $\frac{1}{2}$ mile to the north at approximately the same time.

*Pictures of hail damage in these cases are shown in figures 18 to 21.

TABLE IV.- INCOMPLETE CASE HISTORIES OF HAIL DAMAGE TO TRANSPORT AIRPLANES

Case	Type of airplane	Date	Location	Damage	Weather situation	Additional information
23	Douglas DC-6	June 21, 1948 0100 CST	SE. South Dakota; Sioux Falls	Appreciable repair needed.	East-west stationary warm front to south.	Flying west.
24	Douglas DC-4	Sept. 7, 1946 About 1400 CST	SW. Nebraska; Hayes Center	Nose, wing, stabilizers, elevators, cowling, navigation lights, and pitot tube.	Northeast-southwest cold front.	Hail 30 sec at 9,000 ft MSL.
25	Douglas *DC-3	May 13, 1940 After 2200 MST	SE. Wyoming; Pine Bluffs	Right side of fuselage. Right cabin windows cracked.	Air mass.	Pilot skirting large thunderstorm located on left. Hail fell from extensive overhang. Tangerine-size hail reported on ground nearby.
26	Douglas *DC-3	June 1940	SE. Montana; Miles City	Nose and leading edge of wing. Windshield broken. Engine push-rod housing dented.	Unknown.	Pilot angling into storm, encountered hail for a very short time as he made immediate turn out of the hail area.
27	Douglas *DC-3	April 20, 1944	***WC. Texas; Abilene	Navigational lights broken.	East-west cold front.	None.
28	Douglas *DC-3	June 9, 1944	SW. Texas; Guadelupe Pass	Landing lights and windshield.	Air mass.	None.
29	Douglas *DC-3	March 19, 1945	***SC. Kansas; Anthony	Nearly all components of plane damaged.	Northeast-southwest cold front.	After encountering hail apparently in thunderstorm, pilot made immediate right turn. Hail 40 sec at 10,000 ft MSL.
30	Douglas *DC-3	July 10, 1945 About 1500 EST	E. Pennsylvania; Summit Hill	Wings and stabilizers. Numerous dents all over plane. Engine damage.	Northeast-southwest cold front.	Apparently flew into thunderstorm. Heavy updraft with hail. 15 sec of heavy hail at 9,000 ft MSL.
31	Douglas *DC-3	Aug. 19, 1945 About 0900 MST	S. Wyoming; Between Cheyenne and Salt Lake City	Elevators stripped. Holes in both ailerons; cabin windows cracked on right side. Dents in fuselage.	Air mass or pre-cold frontal activity.	None.
32	Douglas *DC-3	Dec. 24, 1945	***C. Arkansas; Pine Bluff	Landing lights broken.	Northeast-southwest cold front.	None.
33	Douglas *DC-3	March 12, 1946	***SC. Texas; San Antonio	Leading edges of wings and stabilizers. Landing lights broken.	North-south upper cold front.	None.
34	Douglas *DC-3	April 10, 1946	NE. Texas; Dallas	Holes in left elevator.	East-west post cold front.	None.
35	Douglas *DC-3	June 11, 1947	E. Ohio; En route to Pittsburgh	Four tears in upper side of both elevators.	Air mass; maybe stationary front to south.	Through severe hail and thunderstorm.
36	Douglas *DC-3	Aug. 27, 1949 1510 MST	SE. Wyoming; 15 miles N. of Laramie	Windshields and astrodome broken. Minor dents in leading edge of wings and nose.	North-south stationary front.	Sighted rainshower over mountainous terrain while under VFR conditions at 8,500 ft MSL. Encountered hail briefly while circumnavigating shower. Pilot made an immediate turn.
37	Douglas *DC-3	Feb. 21, 1950 1650 CST	***EC. Oklahoma; 80 miles W. of Ft. Smith, Ark.	Paint off propellers.	Northeast-southwest cold front.	Entered mild thunderstorm. Hail only light. No pilot action necessary. Hail for 30 sec at 6,000 ft MSL.
38	Beech **D18S	April 23, 1949 1630 EST	SE. Virginia; Norfolk	Windshield broken. Other damage unknown.	Cold front or pre-frontal squall line.	Other aircraft in same area avoided hail by changing course. Hailstones approximately $\frac{3}{4}$ by $1\frac{1}{2}$ inches observed 6 miles northwest from same storm.

*For evaluation purposes the Douglas airplanes DC-3, C-47, and R4D are all classified as Douglas DC-3.

**For evaluation purposes the Beech airplanes D18S, JRB, and C-45 are all classified as Beech D18S.

***C refers to central.

TABLE V.- INCOMPLETE CASE HISTORIES OF HAIL DAMAGE TO MILITARY AND MISCELLANEOUS AIRPLANES

Case	Type of airplane	Date	Location	Damage	Weather situation	Additional information
39	Boeing B-29	May 17, 1949 1435 CST	**C. Oklahoma; 5 miles NW. of Anadarko	Leading edge of wing and stabilizers. Engine cowlings. Bombardier's window cracked.	Air-mass thunderstorms developed in a north-south line.	Flying west-southwest. Entered IFR conditions 55 miles WSW. of Oklahoma City at 3,000 ft MSL and started to climb. Encountered light rain which changed quickly to light then heavy hail for 2 min between 6,000 and 8,000 ft. Broke into clear at 10,000 ft.
40	Boeing B-17	April 1, 1949 1930 CST	Gulf of Mexico; 450 miles SW. of Mobile, Ala.	Minor dents on fairings and propeller. Windshield and astrodome broken.	Northeast-southwest cold front.	Flying northeast. Engine power was reduced and other precautions taken before entering cold front. Encountered moderate turbulence and heavy rain, followed by severe turbulence, hail and continuous lightning for 10 min at 5,000 ft MSL.
41	North American B-25	April 6, 1948 1930 CST	**SC. Missouri; 40 miles NE. of Springfield	Nose glass, landing lights and cowling.	Air mass.	VFR clearance through area of severe turbulence for 15 min.
42	North American B-25	June 3, 1949 1500 MST	**NC. New Mexico; 15 miles NE. of Las Vegas	Minor dents in leading edge of wings. Nose plexiglass broken.	East-west cold front.	Flying south under VFR conditions. Thunderstorms forecast en route. Turned left to avoid small rain shower in front of thunderstorm at 9,000 ft MSL. Encountered hail for 15 sec in clear. Storm center estimated 4 miles to right with base 5,000 ft above ground. Cut power and made 180° turn out of hail.
43	North American B-25	July 15, 1949 1820 CST	SE. Colorado; 10 miles W. of Arlington	Leading edge of wings and stabilizers. Nose and engine cowlings. Pilot canopy broken.	Air mass.	Flying northwest under VFR conditions at 7,500 ft MSL. Thunderhead observed 10 miles ahead. When 3 miles from nearest cloud, hail was encountered for 30 to 45 sec. Pilot made a shallow diving turn to left.
44	North American B-25	Oct. 10, 1949 1300 CST	N. Texas; 30 miles NE. of Pampa	Nose and all leading edges of wing and stabilizers. Various glass light covers broken.	Northeast-southwest stationary front south-east of area with a second cold front moving in from northwest.	Flying northwest under IFR conditions. Flight at 12,000 ft MSL between stratus-cloud decks and then into stratus. Strong cross wind from left. Encountered rain, changing to sleet and snow, with mild turbulence changing to moderate, then into hail with heavy rain and snow. Updraft carried plane to 15,000 ft, then in downdraft to 8,000 ft, then in updraft to 13,000 ft. Violent turbulence and hail for 3 to 4 min. During these severe conditions pilot made 180° turn and returned to 12,000 ft.
45	Lockheed F-80	May 31, 1949 1530 CST	N. Louisiana; 10 miles W. of Ruston	Control surfaces, intake ducts, and stabilizers damaged. Lightning damaged trailing edge of right horizontal stabilizers.	Air mass.	Four planned penetrations of a thunderstorm were made over a 40-min period to test equipment. Altitude 24,500 to 25,000 ft MSL; IAS 230 to 300 mph. Lightning and moderate turbulence. Hail was not detected during flight and no unusual noise was heard. VHF equipment was not affected by electrical disturbances.
*46	Cessna Bobcat type	April 9, 1944	N. Texas; Pampa	Wood and/or fabric of 196 aircraft damaged.	North-south cold front.	Base organizations warned of high winds. Hangar space not available. Hail 1 in. in diameter for 60 sec.
*47	2 - Douglas DC-4 2 - Douglas DC-3 9 - Consolidated Vultee BT-13	May 13, 1946	NE. Texas; Ft. Worth	Holes in elevators and stabilizers.	Northeast-southwest stationary front south-east of area.	None.

*Damaged on ground.
**C refers to control.

TABLE VI.- ADDITIONAL CASE HISTORIES OF HAIL DAMAGE TO AIRPLANES

Case	Type of airplane	Date	Location	Damage	Altitude (ft MSL)	Additional information
101	Boeing B-50	May 8, 1950 1930 EST	*EC. Nebraska; 20 miles S. of Omaha	Substantial - 13 pictures of damage available.	6,500	IFR Clearance: Hail encountered during climb after take-off.
102	Boeing B-50	June 12, 1950 0100 MST	SE. South Dakota; 6 miles NNW. of Souix Falls	Substantial - 20 pictures of damage available.	15,000	IFR Clearance: Hail encountered during climb through cold front with radar in operation.
103	Boeing B-29	June 11, 1951 1730 CST	*EC. Texas; 40 miles N. of Waco	Substantial - No pictures available.	12,500	IFR Clearance.
104	Boeing B-29	Aug. 31, 1951 1635 CST	*C. Kansas; Kanopolis	Substantial - No pictures available.	25,000	IFR Clearance: Circumnavigating thunderstorm with radar in operation; windshield damage caused decompression of cabin.
105	Boeing B-29	Feb. 1, 1952 1630 CST	*C. Texas; 10 miles WSW. of Cleburne	Substantial - 7 pictures of damage available.	19,000	IFR Clearance: Radar in operation; windshield damage caused decompression of cabin.
106	North American B-25	Feb. 12, 1950 2103 CST	NE. Texas; 15 miles W. of Dallas	Substantial - 4 pictures of damage available.	6,000	IFR Clearance.
107	North American B-25	May 11, 1950 1540 MST	W. Texas; 30 miles E. of El Paso	Substantial - 7 pictures of damage available.	12,000	IFR Clearance.
108	North American B-25	May 13, 1950 1735 CST	*C. Texas; 5 miles WNW. of Abilene	Substantial - 11 pictures of damage available.	5,000	IFR Clearance.
109	North American B-25	June 20, 1950 1535 CST	*C. Oklahoma; 24 miles S. of Enid	Substantial - 5 picture of damage available.	3,500	VFR Clearance: Circumnavigating under cumulonimbus cloud.
110	North American B-25	June 21, 1951 1956 MST	*EC. Colorado; 70 miles ESE. of Denver	Substantial - 6 pictures of damage available.	5,600	IFR Clearance.
111	North American B-25	Sept. 11, 1951 2010 CST	W. Texas; 50 miles SSE. of Wink	Substantial - 4 pictures of damage available.	9,000	VFR Clearance.
112	Douglas B-26	May 11, 1950 1420 MST	*SC. New Mexico; 30 miles N. of El Paso, Texas	Substantial - 6 pictures of damage available.	6,000	VRF Clearance.
113	North American F-51	Mar. 24, 1950 1820 CST	*C. Alabama; Birmingham	Substantial - 4 pictures of damage available.	Unknown	IFR Clearance changed to VFR: Hail encountered during descent from 22,000 ft.
114	Lockheed F-80	May 19, 1950 1540 EST	S. South Carolina; 30 miles N. of Savannah	Substantial - 6 pictures of damage available.	30,000	VFR Clearance changed to IFR: Hail encountered in the vicinity of cold front.
115	Republic F-84	Apr. 3, 1950 1108 CST	*WC. Arkansas; Fort Smith	Substantial - 6 pictures of damage available.	23,000	IFR Clearance.
116	Republic F-84	June 5, 1951 1420 MST	*EC. New Mexico 50 miles W. of Tucumcari	Substantial - 5 pictures of damage available.	25,000	VFR Clearance changed to IFR: Two aircraft in formation flight.

*C refers to central.

TABLE VI.- ADDITIONAL CASE HISTORIES OF HAIL DAMAGE TO AIRPLANES - Concluded

Case	Type of airplane	Date	Location	Damage	Altitude (ft MSL)	Additional information
117	Republic F-84	June 5, 1951 1420 MST	*EC. New Mexico; 50 miles W. of Tucumcari	Substantial - 5 pictures of damage available.	25,000	VFR Clearance changed to IFR: Two aircraft in formation flight.
118	North American F-86	June 19, 1951 1520 EST	N. Maine; 5 miles NW. of Limestone	Substantial - 5 pictures of damage available.	8,000	VFR Clearance.
119	Beech AT-7	Apr. 21, 1951 1550 CST	*SC. Louisiana; 25 miles E. of Lafayette	Substantial - 5 pictures of damage available.	8,000	IFR Clearance.
120	Beech AT-11	May 23, 1951 1810 CST	W. Texas; 20 miles W. of Sanderson	Substantial - 4 pictures of damage available.	2,900	VFR Clearance.
121	Lockheed T-33	Sept. 1, 1951 1415 CST	SE. Alabama; Troy	Substantial - 6 pictures of damage available.	30,000	IFR Clearance.
122	Beech C-45	Aug. 21, 1950 1635 MST	*C. New Mexico; 20 miles SW. of Las Vegas	Substantial - 5 pictures of damage available.	7,000	VFR Clearance.
123	Curtis C-46	May 14, 1950 1610 CST	*EC. Mississippi; 15 miles S. of Columbus	Substantial - 10 pictures of damage available.	5,000	IFR Clearance.
124	Fairchild C-82	July 10, 1951 1508 MST	*SC. Wyoming; 20 miles W. of Rawlins	Substantial - 3 pictures of damage available.	12,000	IFR Clearance.
125	Douglas DC-6	Apr. 29, 1950 1200 CST	*C. Louisiana; Baton Rouge	Substantial	14,000	Hail small at first but quickly changed to large stones.
126	Douglas DC-6	May 29, 1950	Unknown (Between Oakland, Calif. and Chicago, Ill.)	Substantial	Unknown	None.
127	Douglas C-39	May 19, 1950 1930 CST	NE. Mexico; 60 miles S. of Victoria	Substantial	6,000	None.
128	Boeing C-97	July 22, 1951 1705 GMT	Luxembourg; 90 miles SW. of Rhein Main Air Base	Substantial - 8 pictures of damage available.	8,000	IFR Clearance from Rhein Main Air Base Germany to Lages Azores TAS 220 mph.
129	Lockheed F-80	May 28, 1951 1635 Korean Time	Japan; Honshu	Substantial - 3 pictures of damage available.	22,000	VFR Clearance.
130	Avro York	July 9, 1949 1705 LST	S. America; S. Brazil	Substantial	8,500	Smooth during hail encounter. Hail began 1 min. after entering "strataform" cloud. Temperature 11° C.
131	De Havilland Mosquito	May 11, 1945 after 1600 GMT	S. England	Substantial	4,500	Hail encountered during descent through a break. 30 sec. in cloud. Stones on ground size of golf balls.

*C refers to central.

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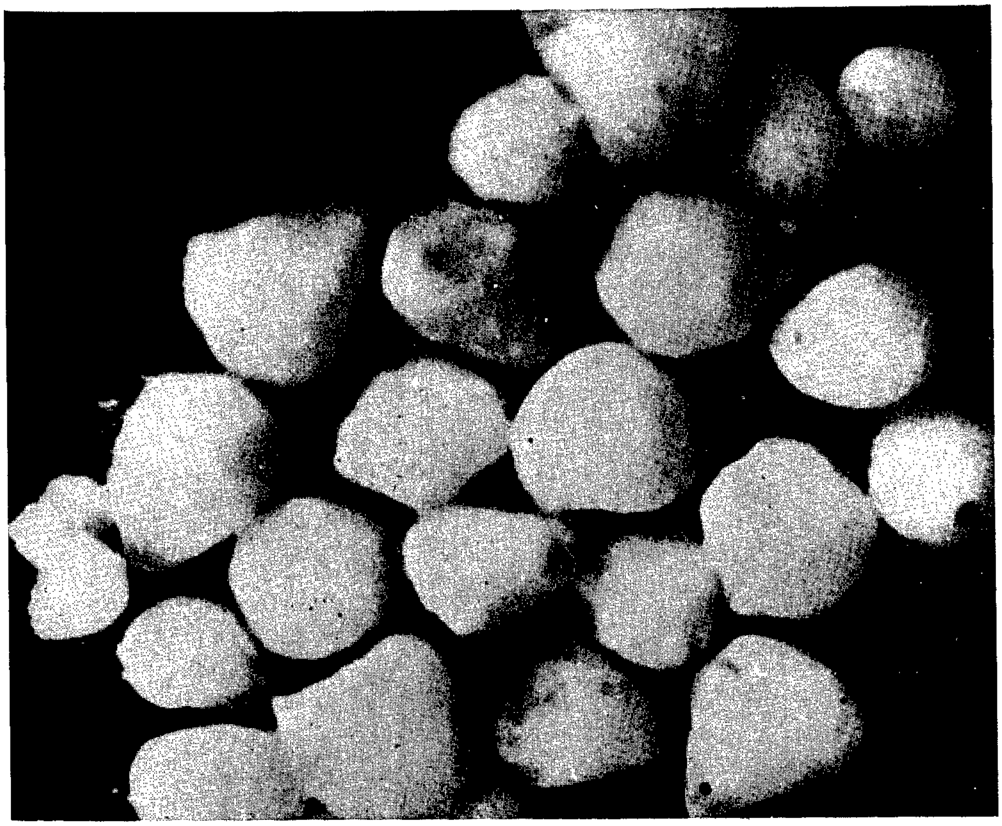
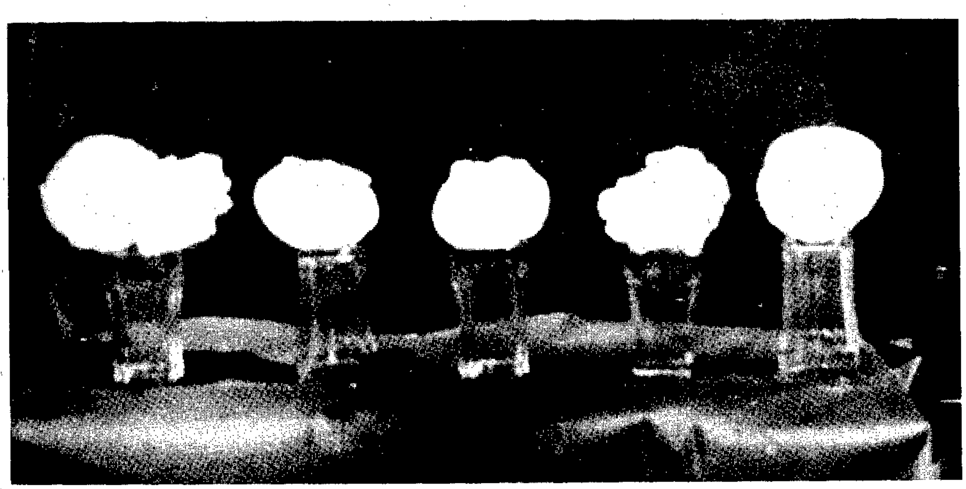


(a) Actual size of hailstones which fell at Washington, D. C., on April 28, 1938. (From reference 5.)



(b) Hailstones which fell at Potter, Nebraska, on July 6, 1928, on 10-ounce glass tumblers. Hailstone at extreme right measured 17 inches in circumference (5.4 inches in diameter) and weighed $1\frac{1}{2}$ pounds. (From reference 6.)

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Figure 1.- Photographs of typical forms of large hailstones.

(c) Hailstones which fell in Czechoslovakia on June 13, 1946.
(From unpublished manuscript by Dr. Helmut Weickmann.)

Figure 1.- Concluded.

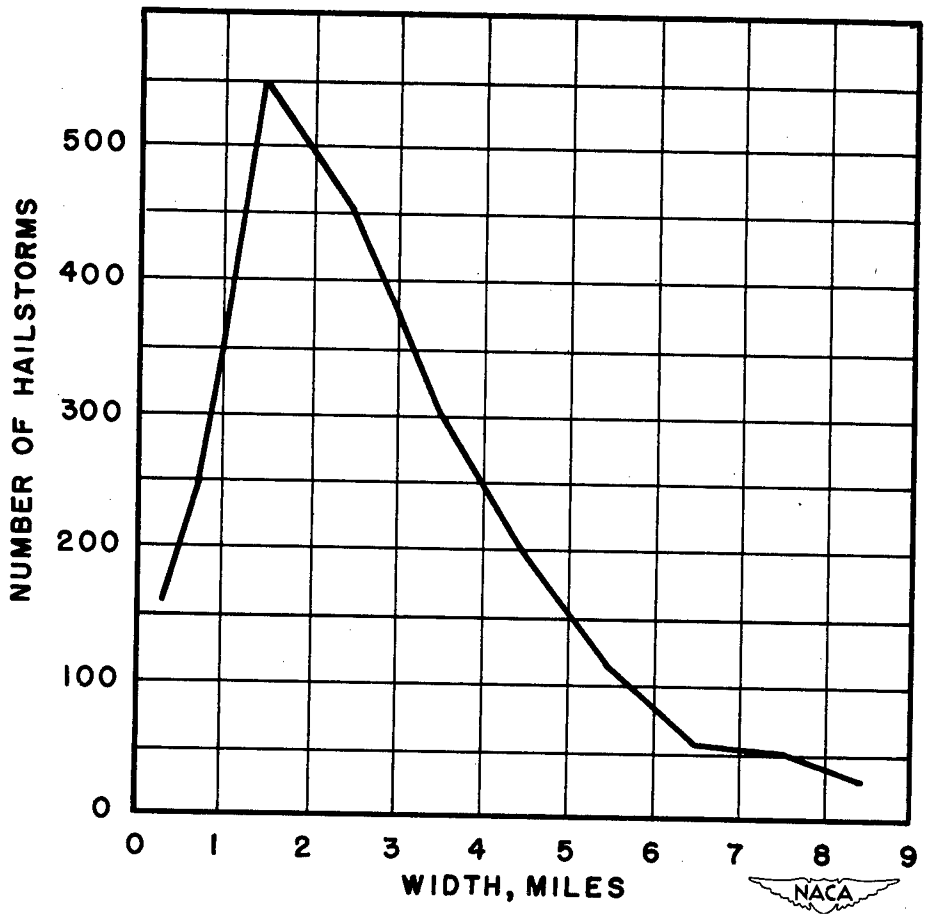
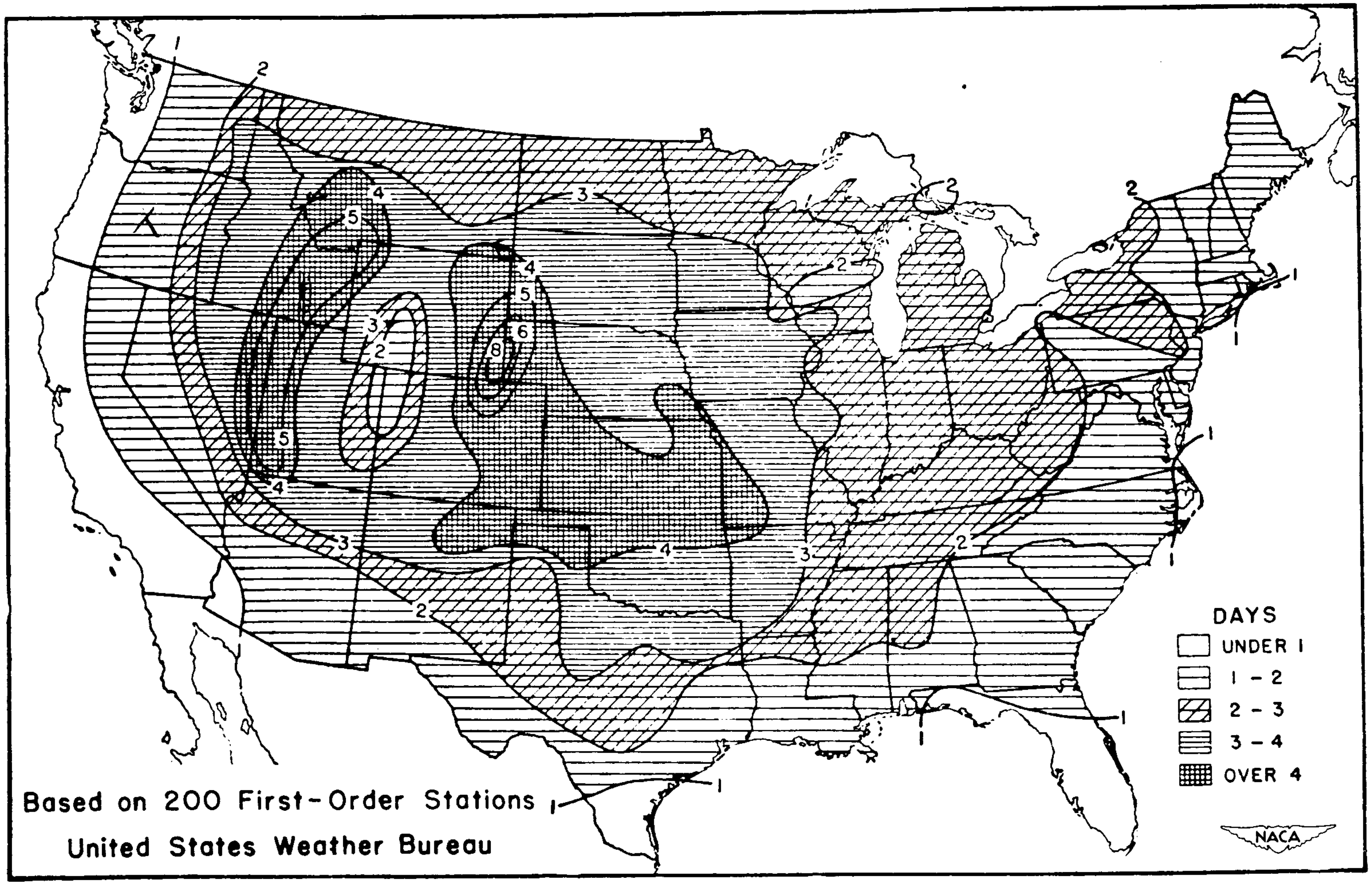
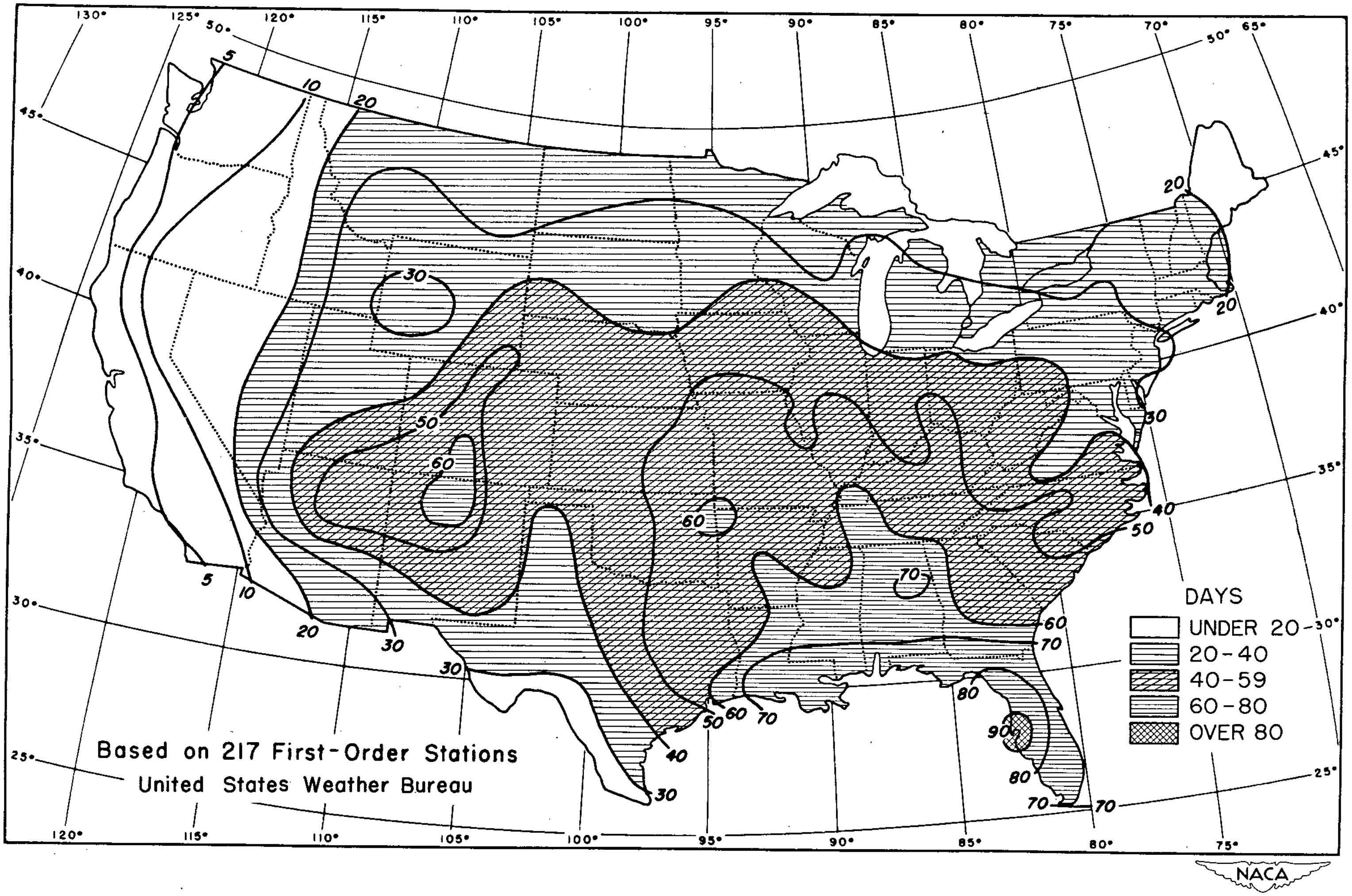


Figure 2.- Width of path of damaging hailstorms based on 2105 hailstorms from 1924 to 1939. (From reference 10.)



(a) Average annual number of days with hail for years 1899 to 1938.
(From reference 13.)

Figure 3.- Annual hail distribution and thunderstorm distribution over continental United States.



(b) Average annual number of days with thunderstorms for years 1904 to 1943. (From reference 12.)

Figure 3.- Concluded.

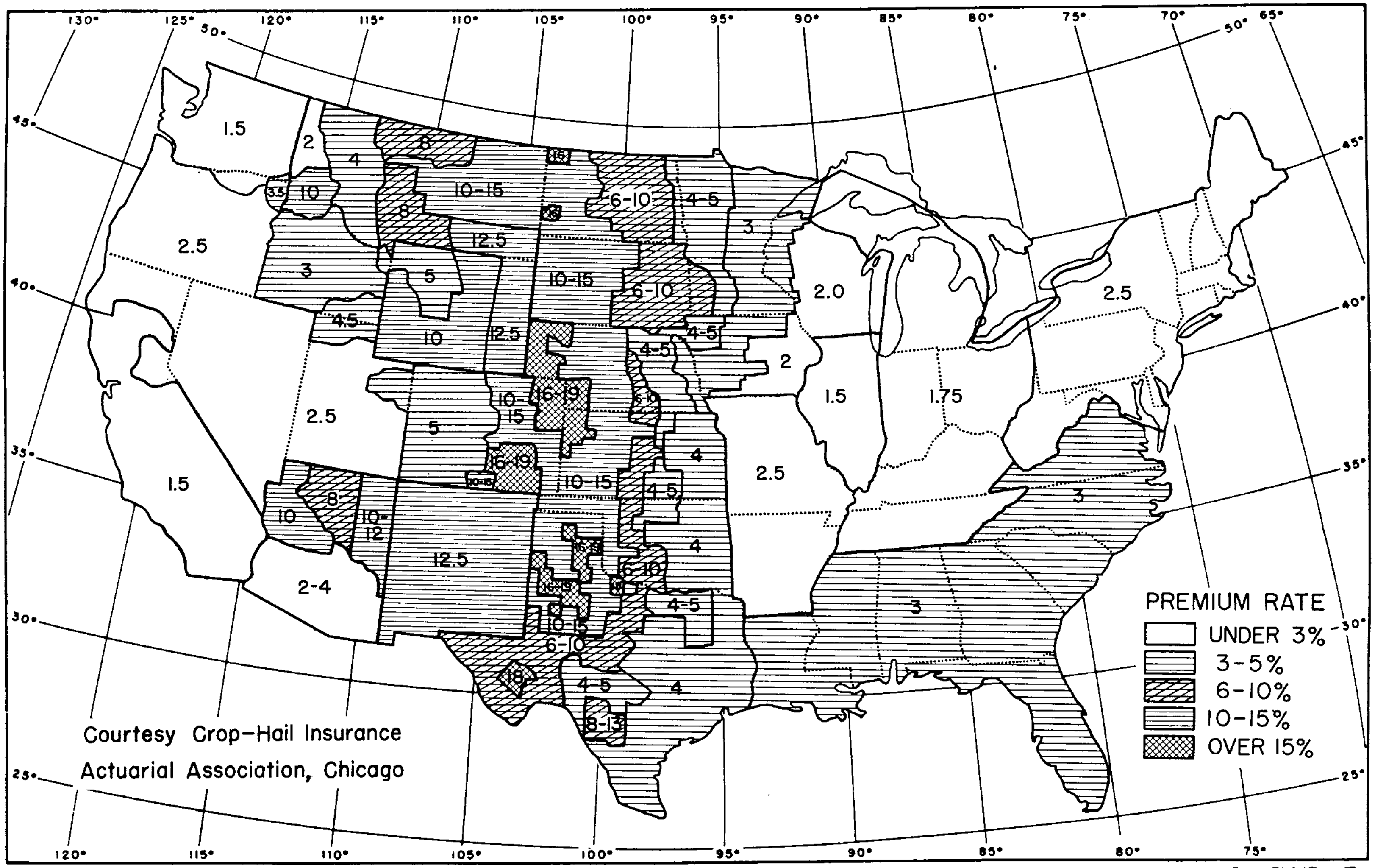


Figure 4.- The 1950 crop-hail insurance rates. (Rates shown are for basic crops such as wheat, oats, corn, and so forth, and are adjusted to uniform policy basis.)

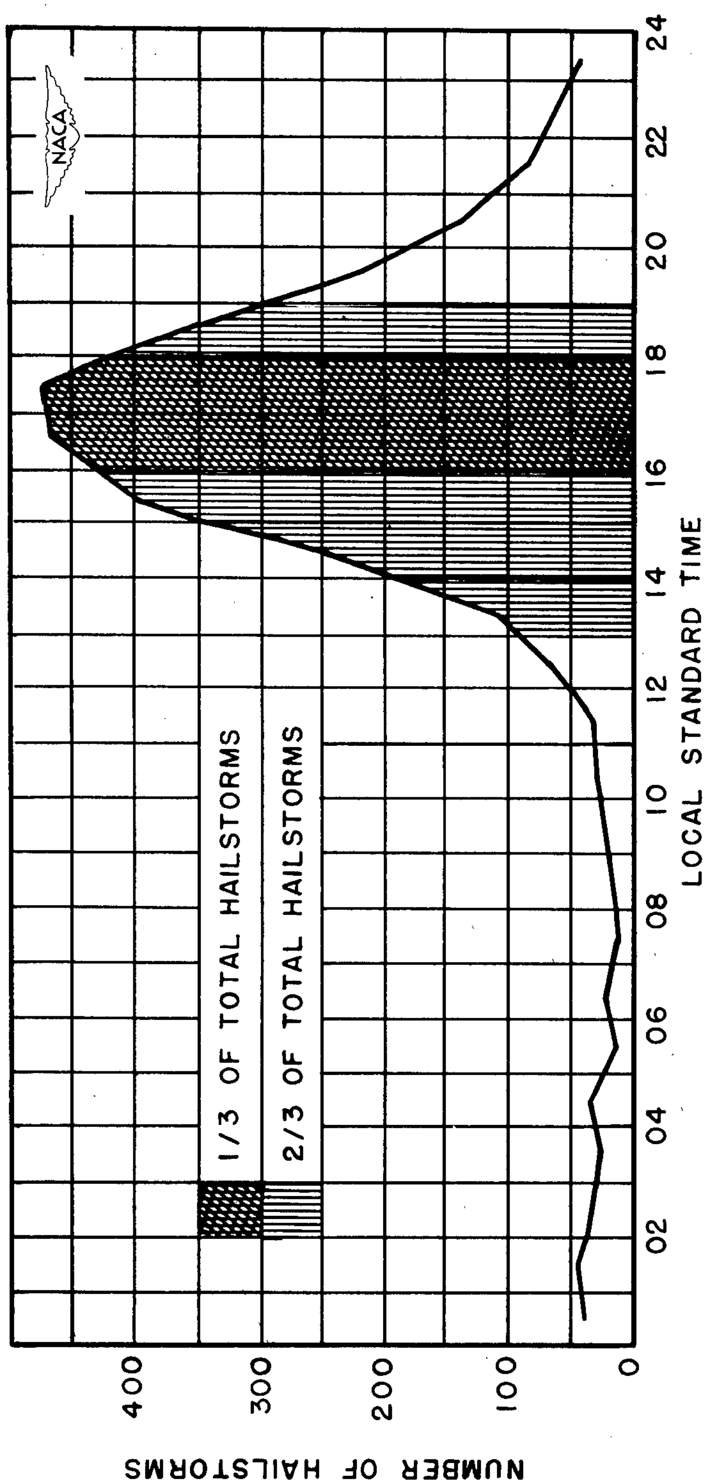
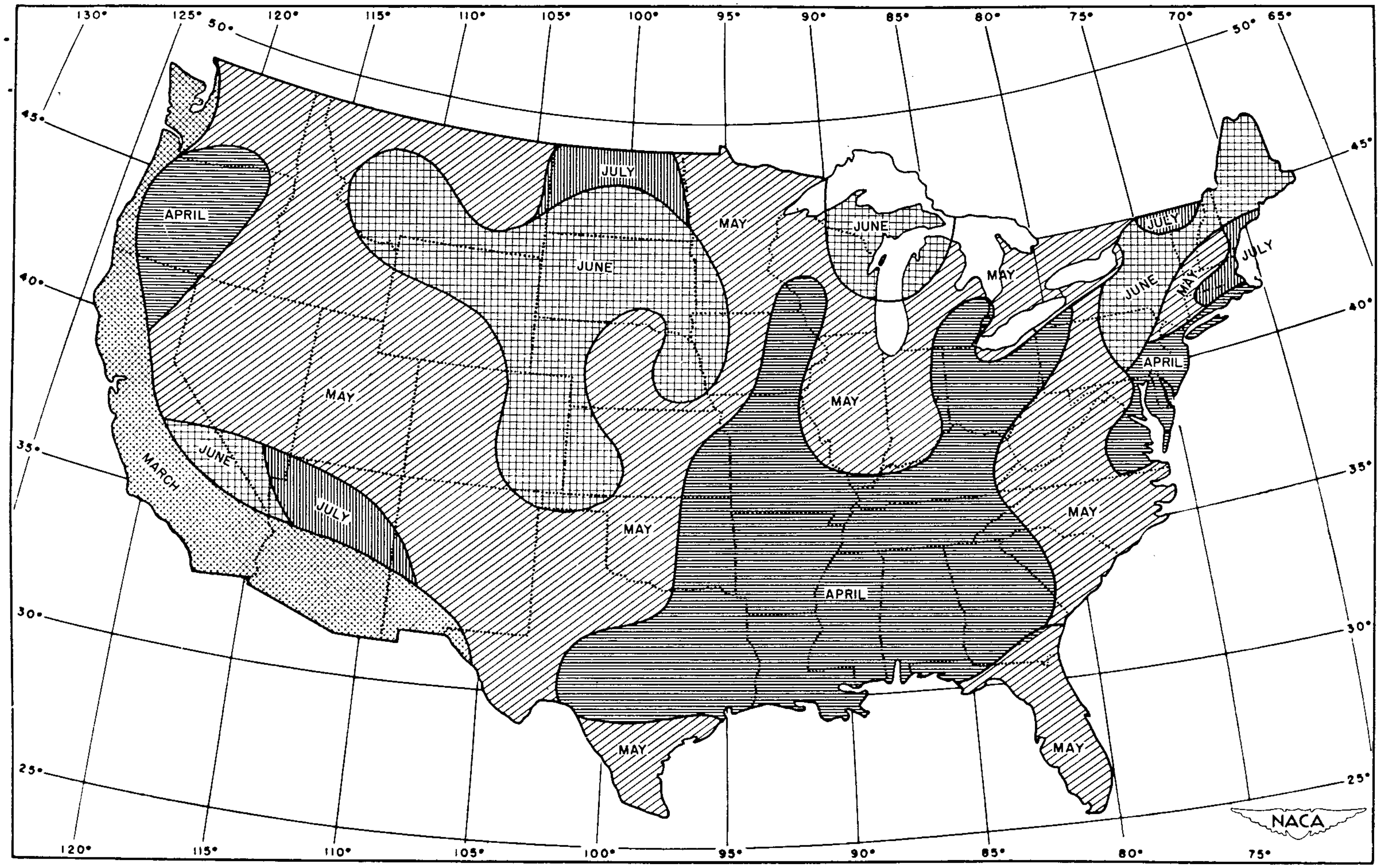
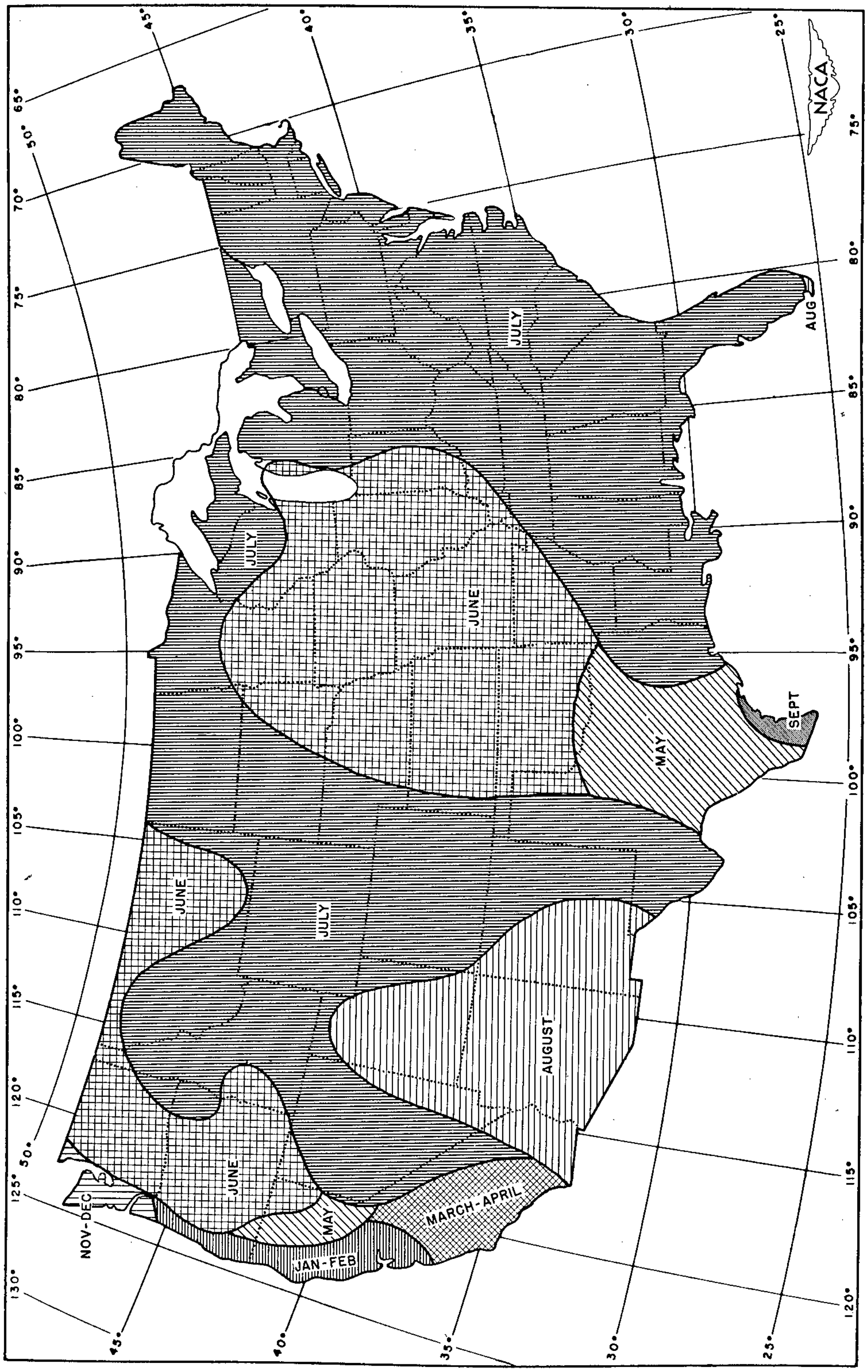


Figure 5.- Hourly distribution of damaging hailstorms. Based on 2335 hailstorms from 1924 to 1939. (Adapted from reference 10.)



(a) Hailstorm distribution.

Figure 6.- Geographical distribution of the months normally having the most hailstorms and those having the most thunderstorms. (Adapted from reference 12.)



(b) Thunderstorm distribution.

Figure 6.- Concluded.

Figure 7.- Hail 2 feet deep which fell during a thunderstorm at Trinidad, Colorado, June 14, 1937. (From reference 20.)

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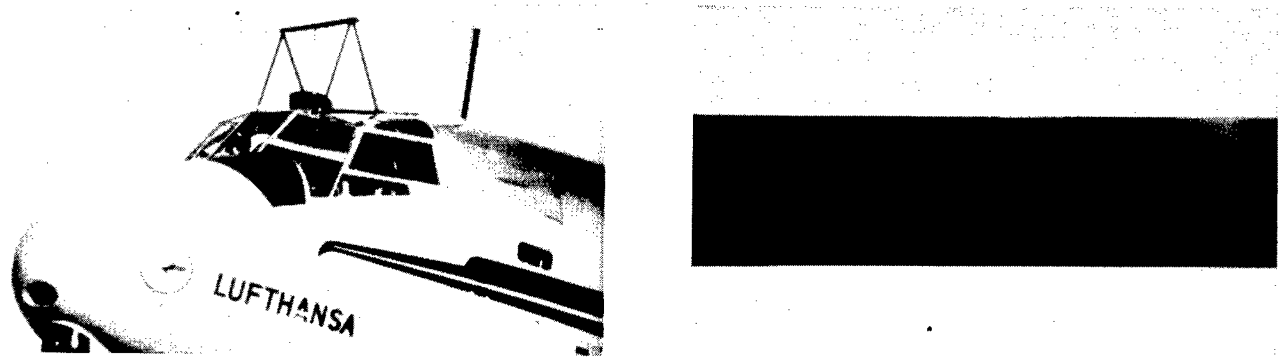

(a) Ice collection rake located over cockpit.

(b) Three cylinders of collection rake as seen from inside of cockpit.

Figure 8.- Photographs of the ice collection rake used in German ice research on Junker Ju 90 aircraft.

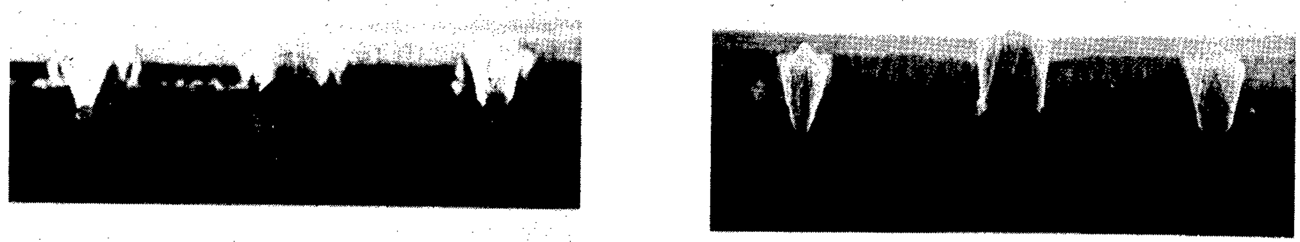

Figure 9.- Opaque ice deposits obtained in strato-cumulus clouds at temperature of -13° C. Cloud-droplet radius, 4.5 microns.

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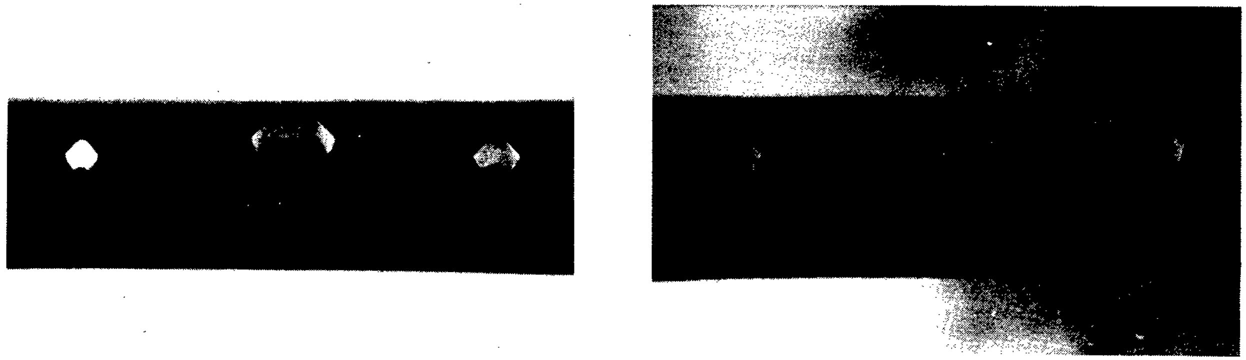

Figure 10.- Opaque ice deposits obtained in alto-cumulus clouds at temperature of -13° C. Cloud-droplet radius, 5 to 7 microns.

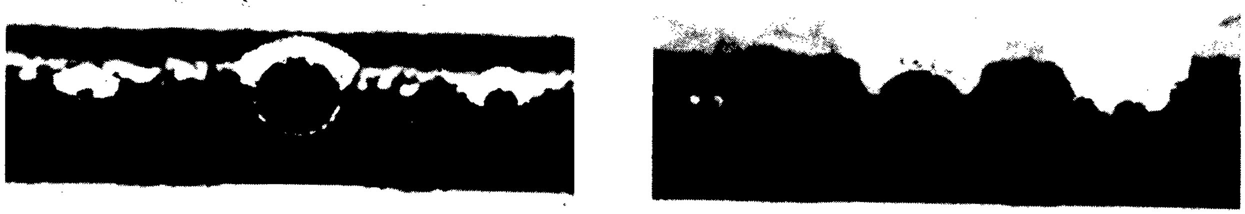

Figure 11.- Clear ice deposits obtained in the upper part of stratus clouds near 0° C. Cloud-droplet radius, 8 to 9 microns.

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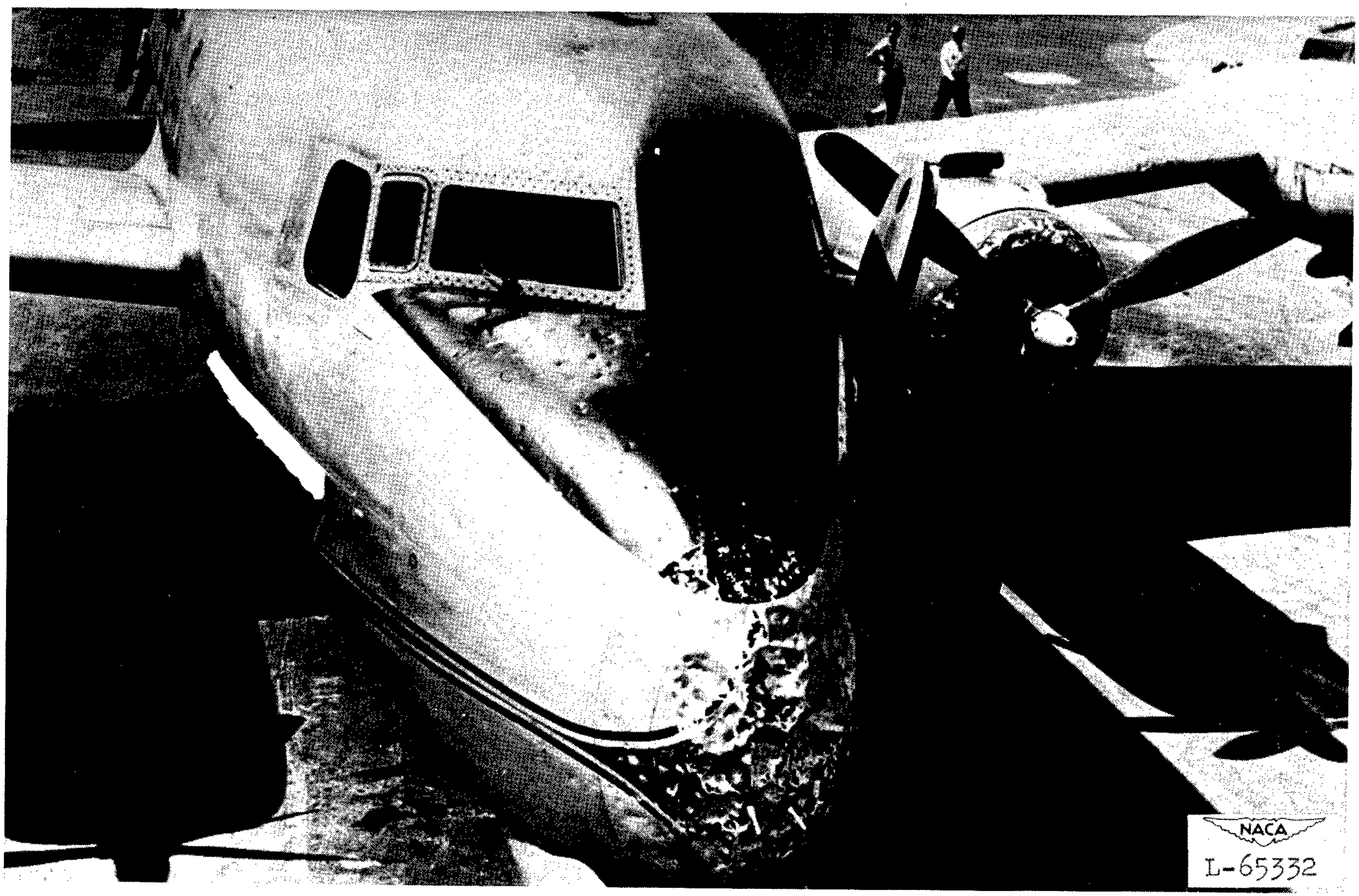
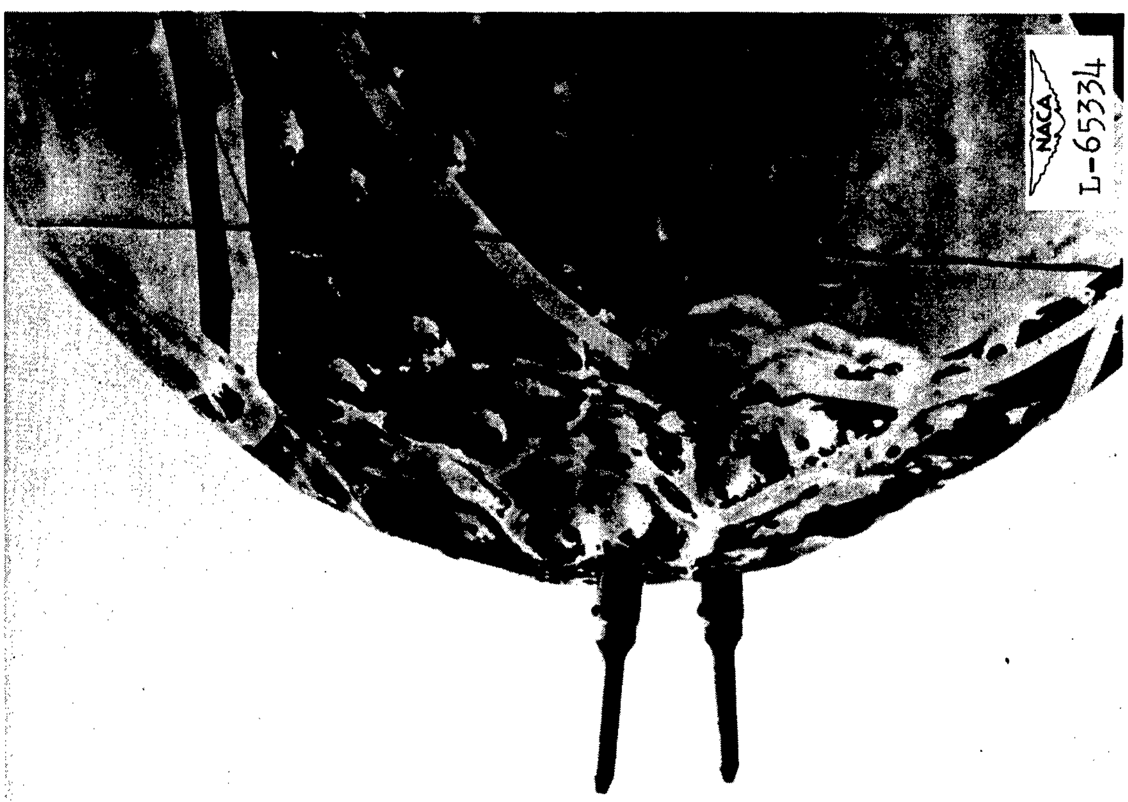


(a) Nose section, fuselage over cockpit, engine cowling 2, and spinner.

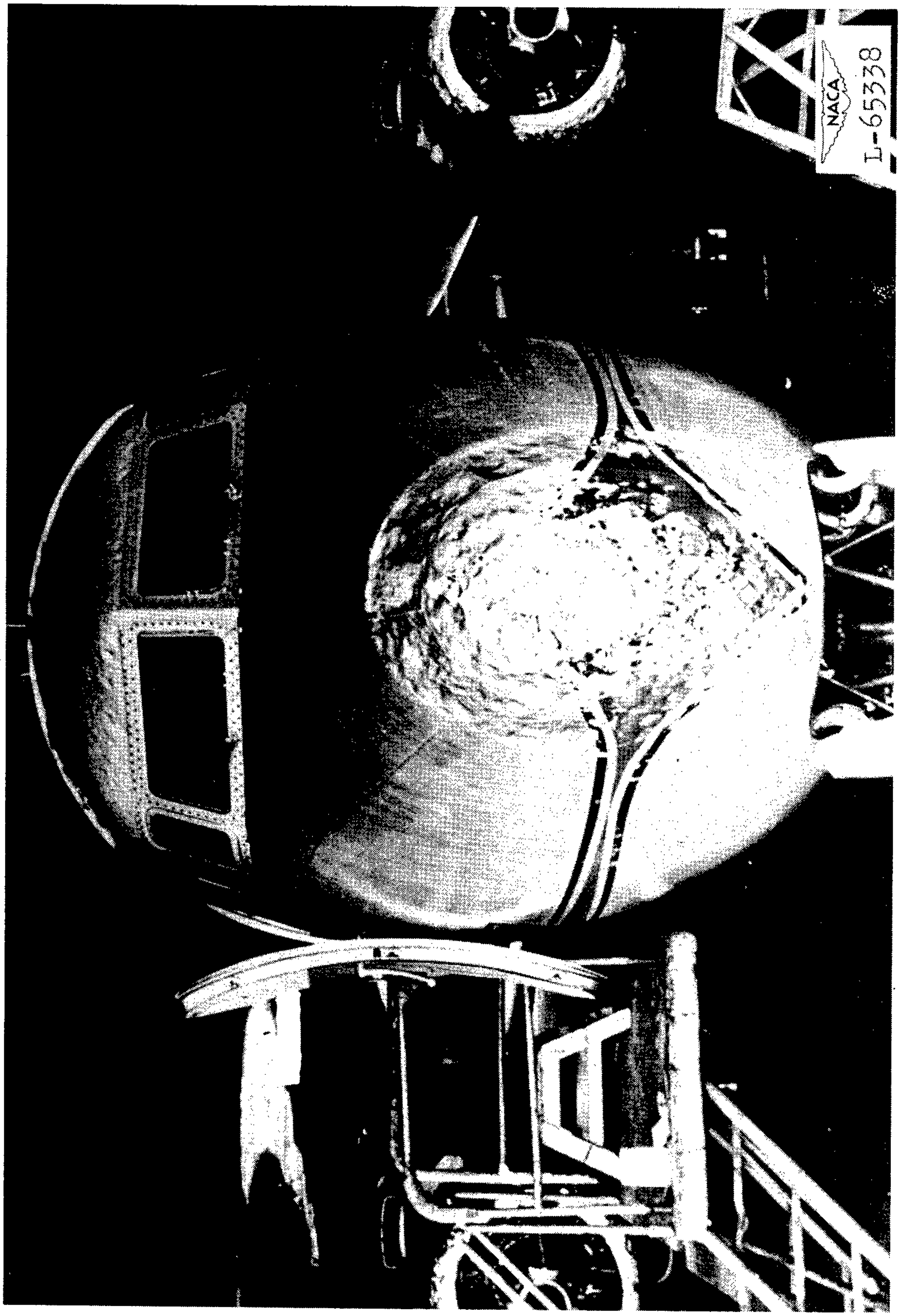
Figure 12.- Hail case 1. DC-6 airplane. (Time in hail 15 sec; TAS 270 mph.)



(b) Nose cap.

(c) Cowling.

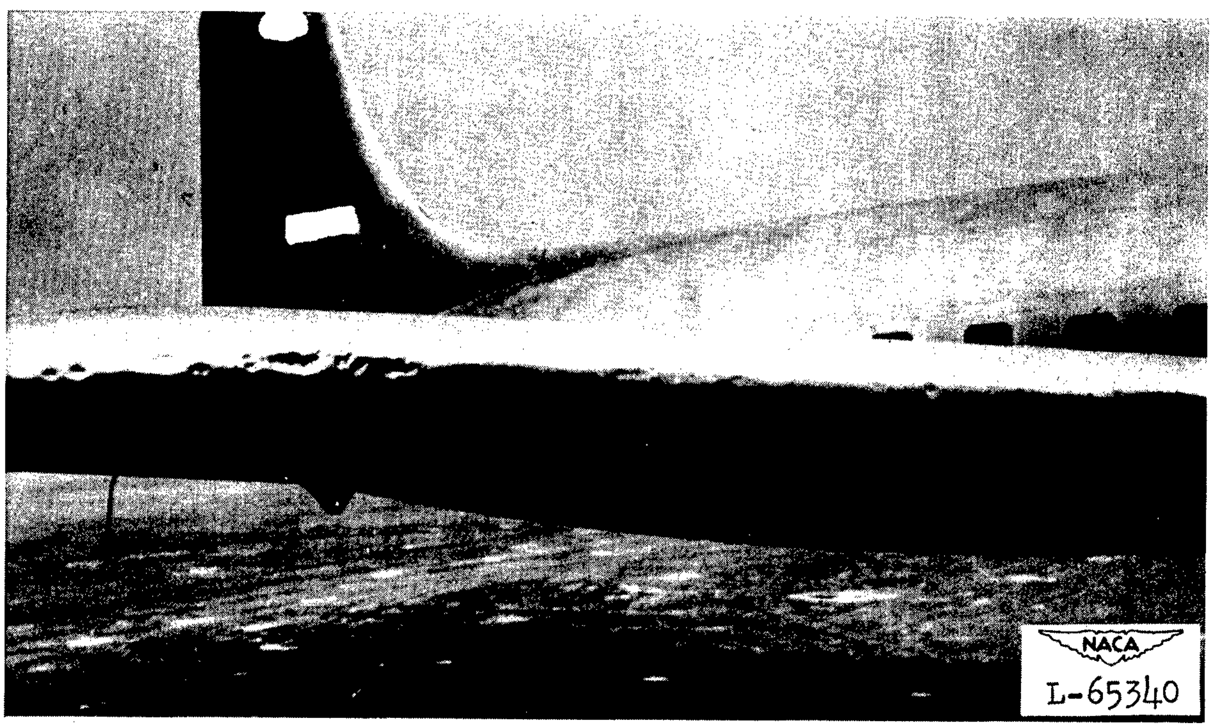
Figure 12.- Concluded.



(a) Nose section, fuselage over cockpit, and engine cowlings 2 and 3.

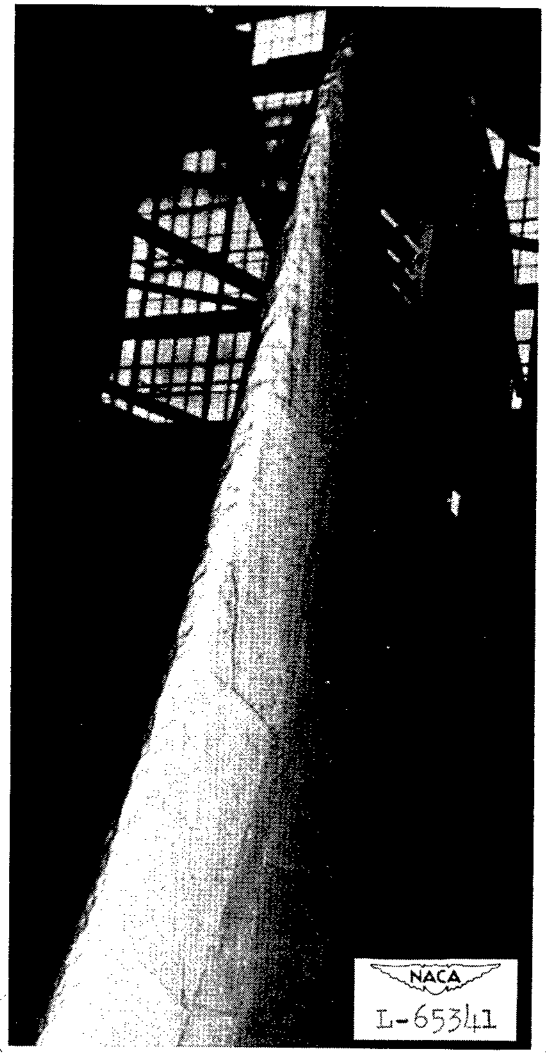
Figure 13.- Hail case 3. DC-6 airplane. (Time in hail 2 to 3 min; TAS 295 mph.)

(b) Left wing.

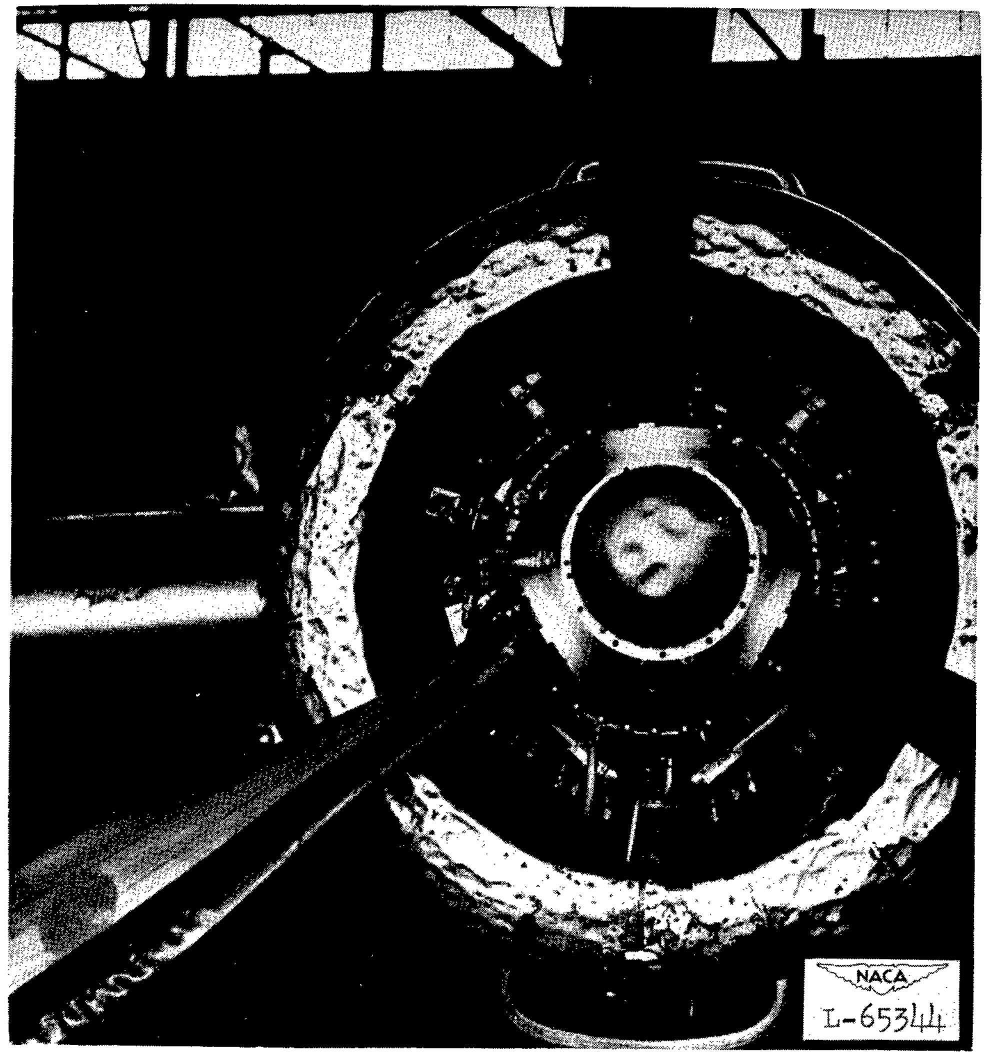


(c) Right wing.

Figure 13.- Continued.

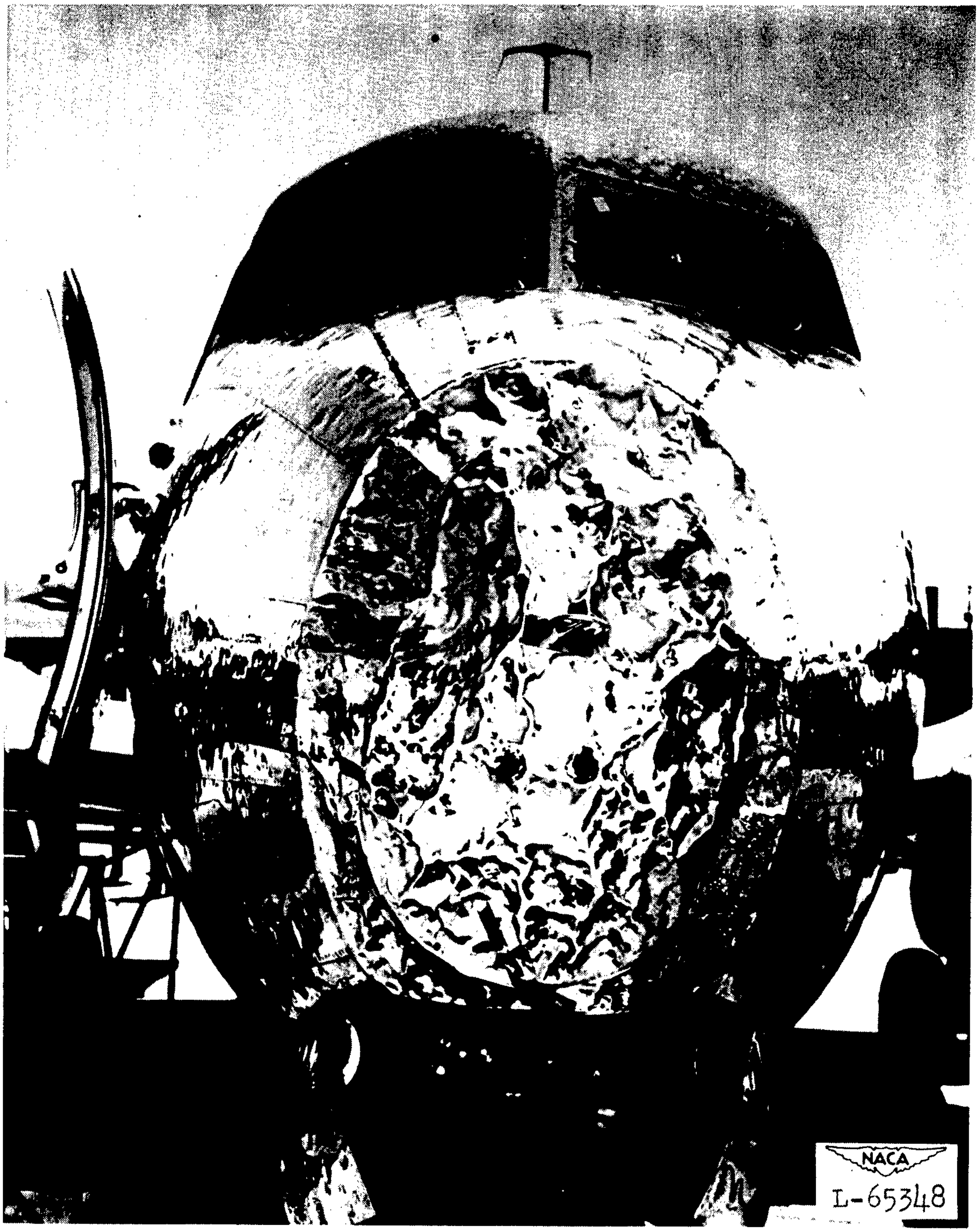


(d) Vertical stabilizer.



(e) **Engine 1. Cowling, spinner,** and propeller.

Figure 13.- Concluded.



(a) Nose section and fuselage above cockpit. (Windshield has been replaced.)

Figure 14.- Hail case 7. DC-6 airplane. (Time in hail 60 sec; TAS 360 mph.)

(b) Engine 3. Cowling and spinner.

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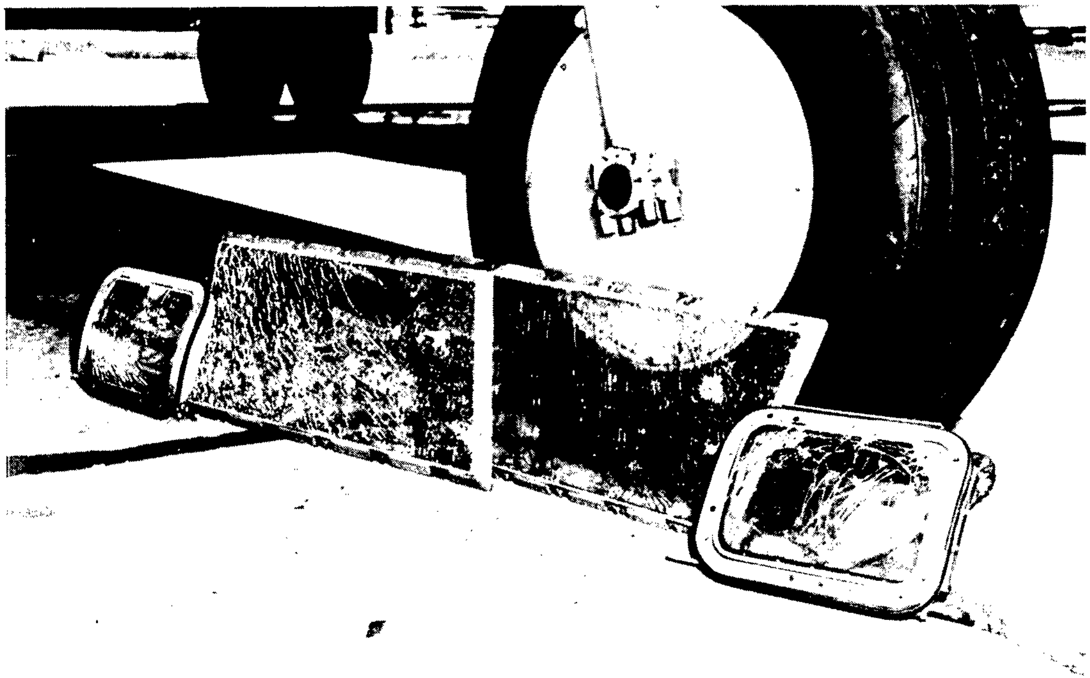
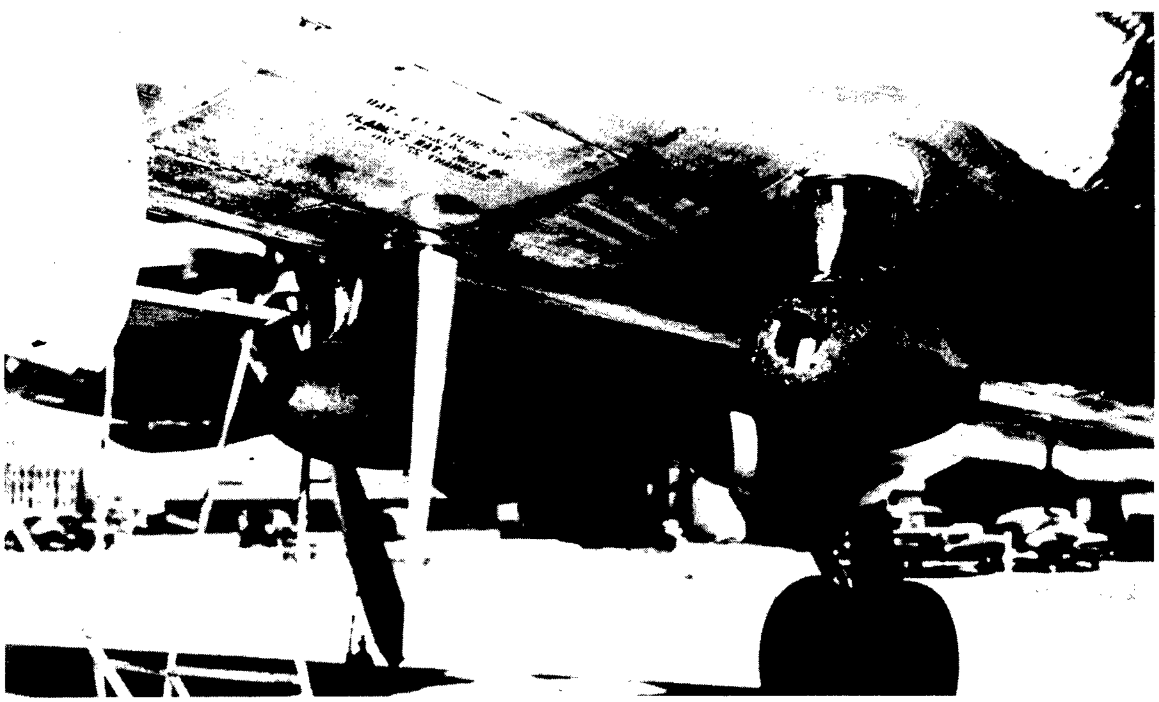
Figure 14.- Continued.



(c) Inner panel of main windshield and curved direct-vision windows.



(d) Loop-antenna housings.

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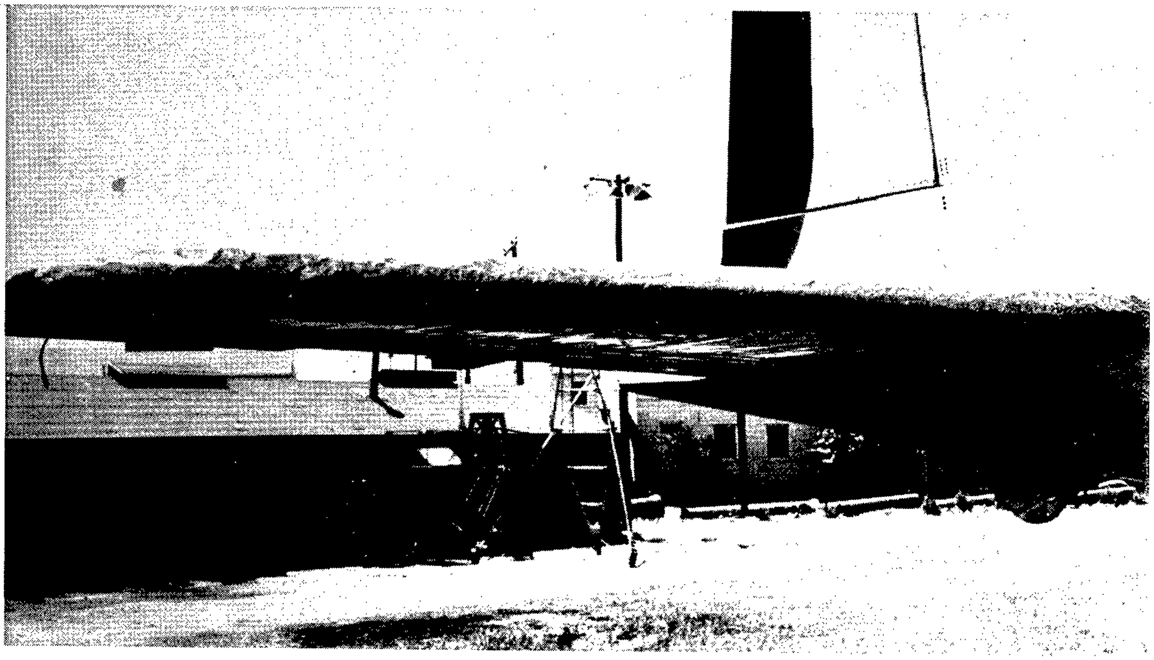
Figure 14.- Continued.



(e) Right horizontal stabilizer.

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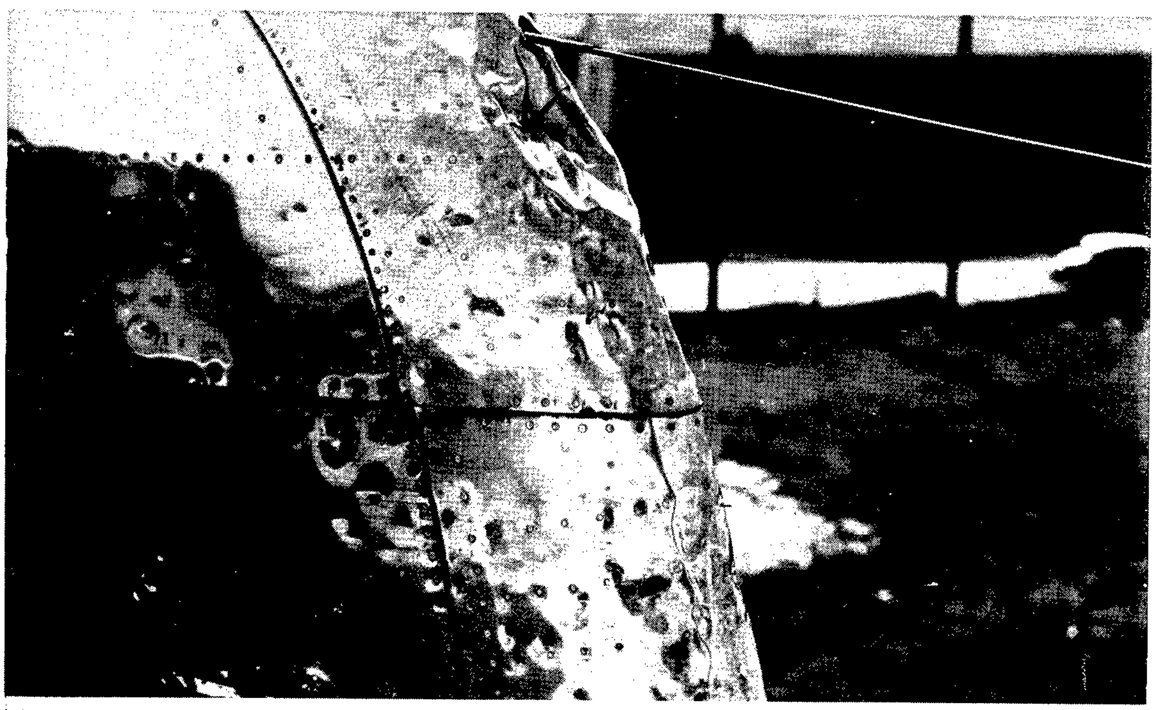
L-65350



(f) Top of vertical stabilizer.

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L-65352

Figure 14.- Concluded.

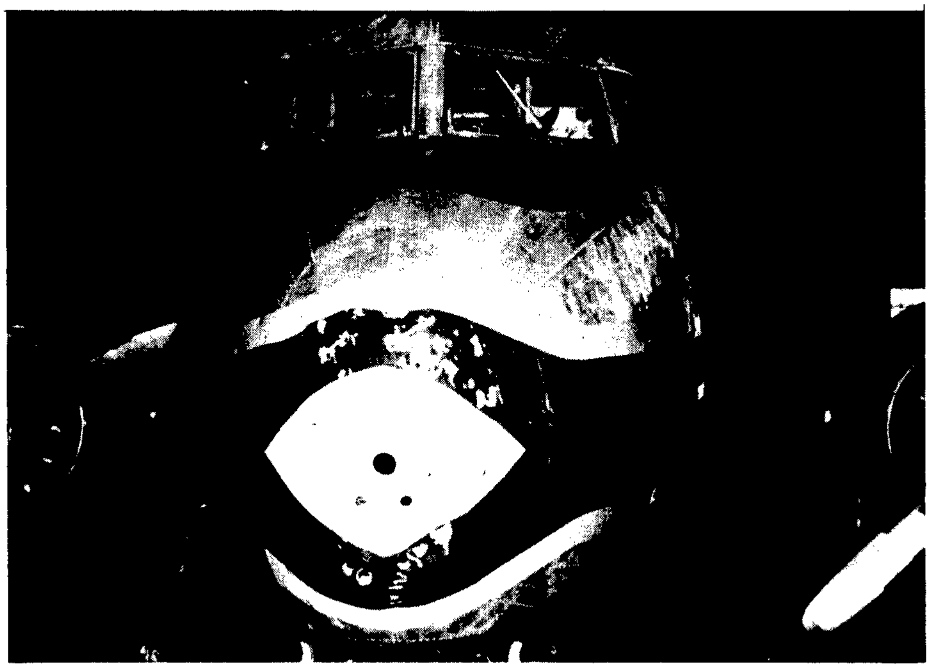

Figure 15.- Hail case 9. DC-4 airplane. Nose section. (Time in hail 8 min; TAS 185 mph.)

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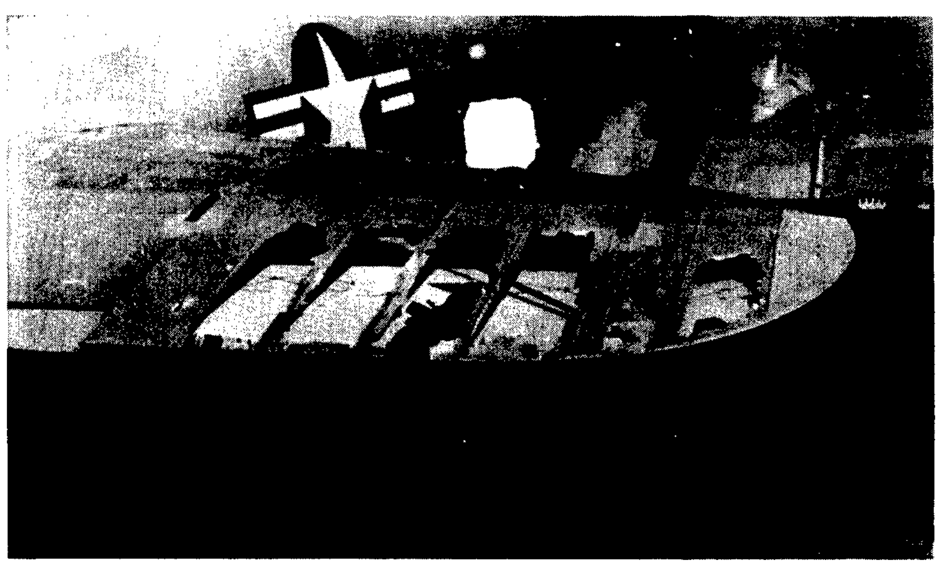

Figure 16.- Hail case 14. DC-3 airplane. Right elevator. (Time in hail unknown; TAS 170 mph.)

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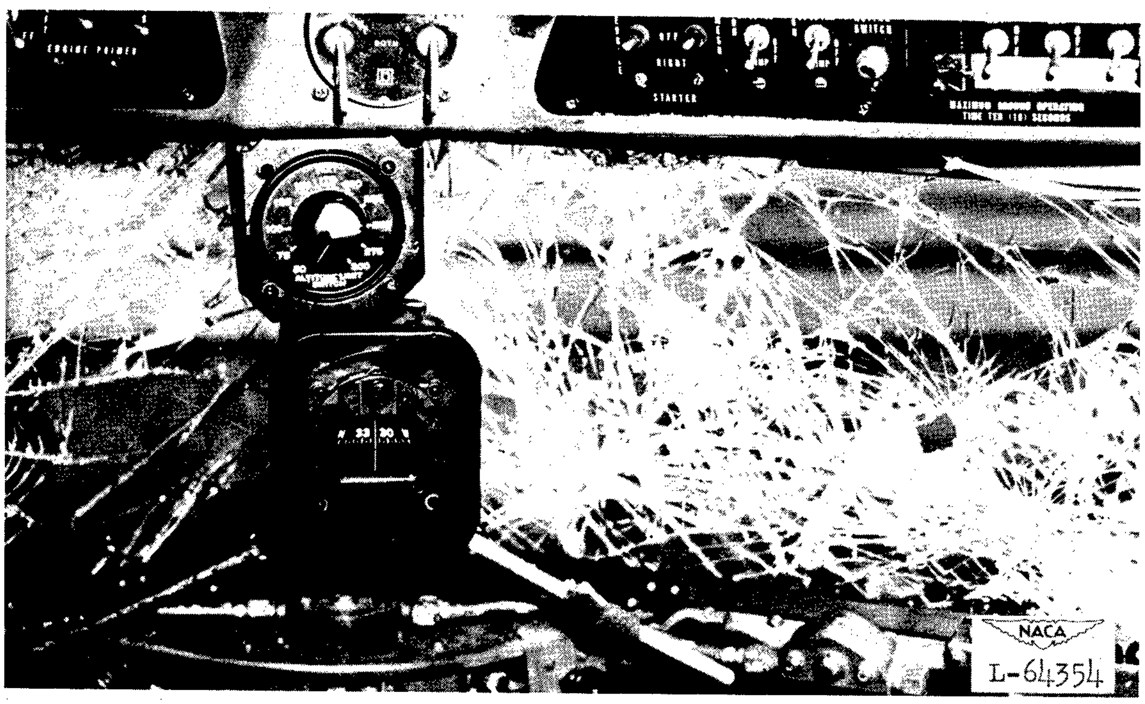
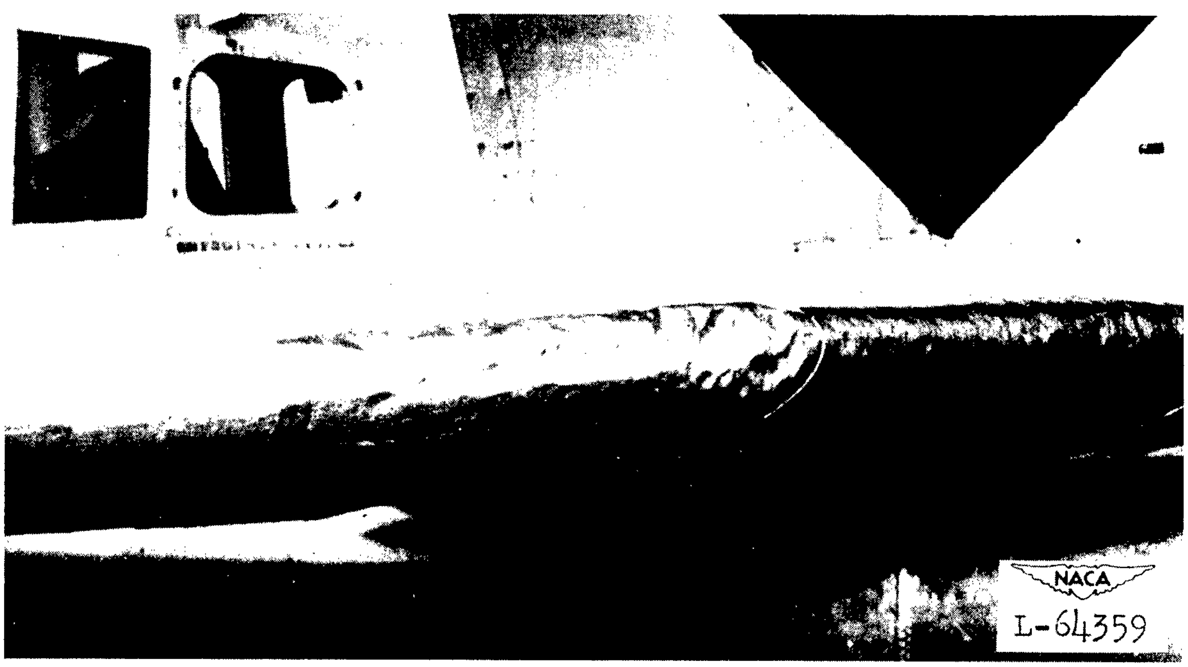
(a) Nose section, windshield, and top of fuselage.



(b) Windshield from inside of cockpit.

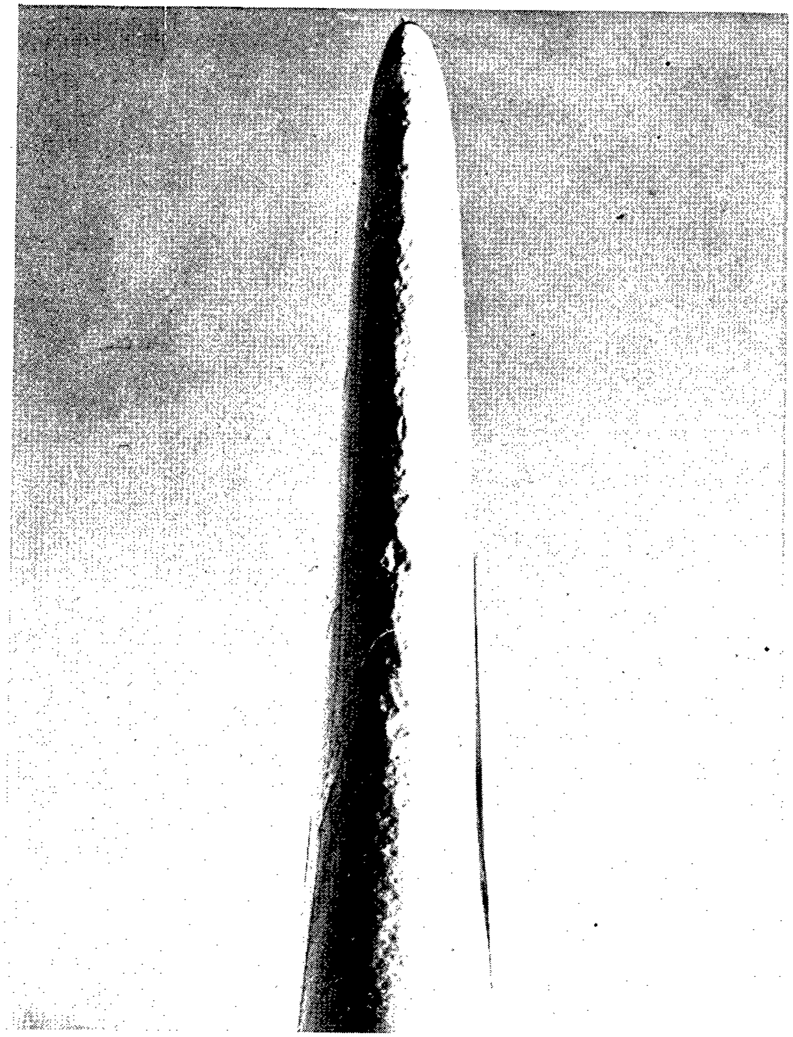
Figure 17.- Hail case 11. DC-3 airplane. (Time in hail 40 sec; TAS 225 mph.)

(a) Leading edge of right wing.



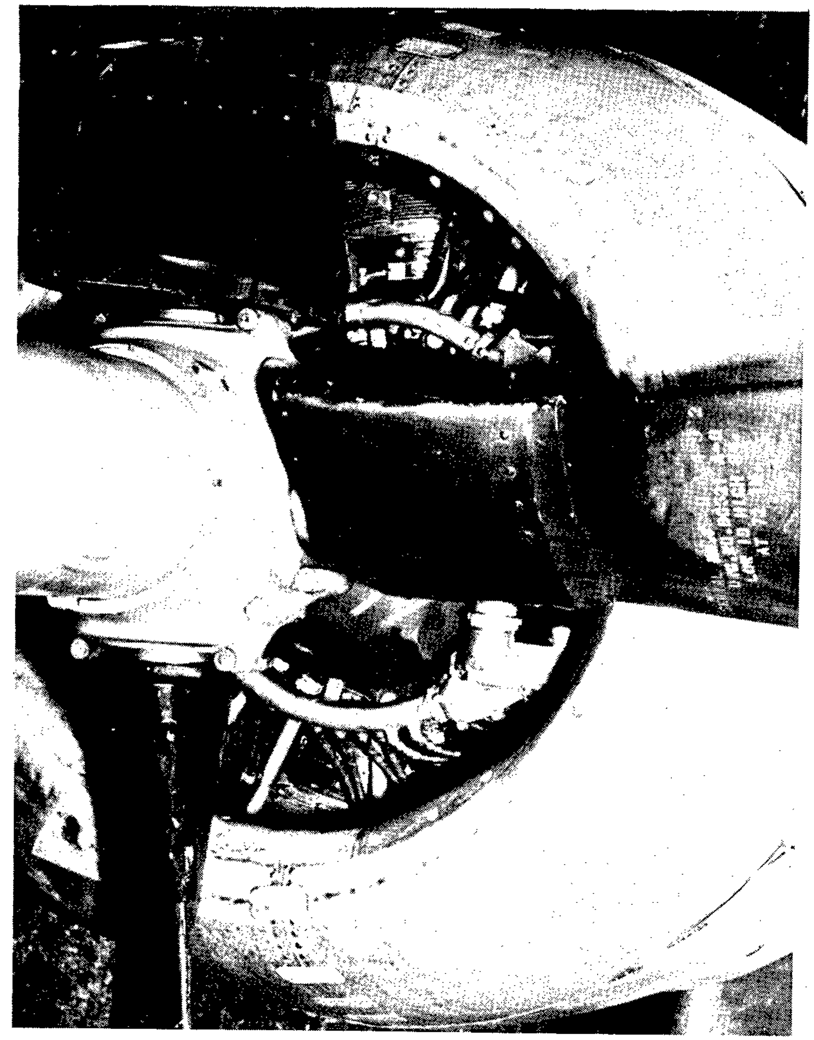
(b) Right horizontal stabilizer.

Figure 18.- Hail case 16. B-29 airplane. (Time in hail 30 sec; TAS 200 mph.)



(c) Vertical stabilizer.

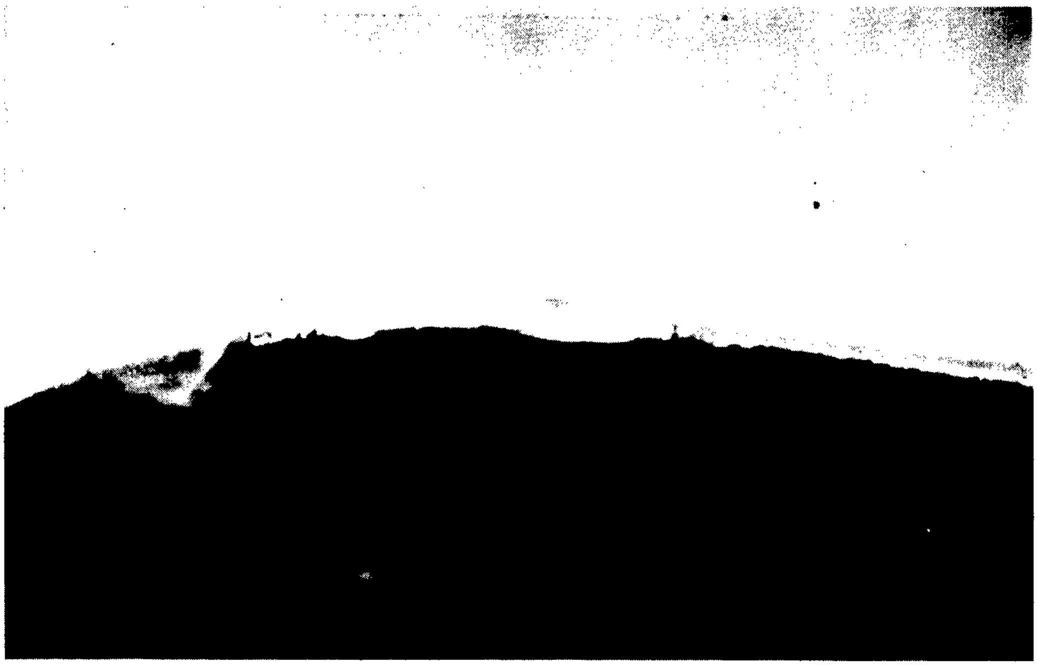
L-64360



(d) Cowling and ignition harness of engine 1.

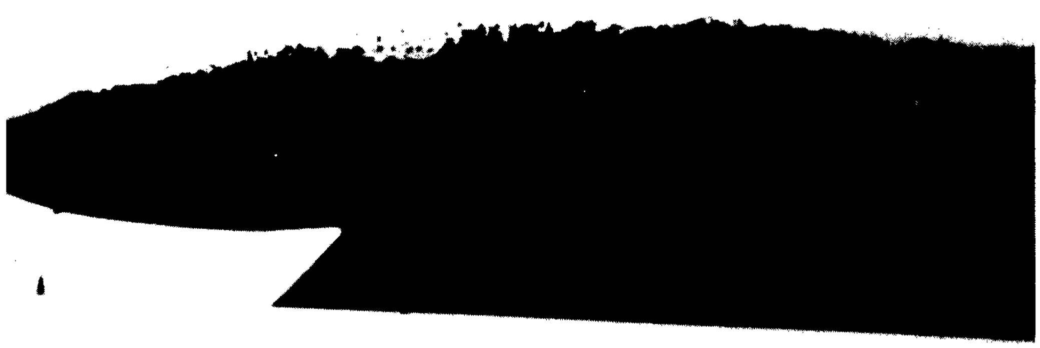
L-64361

Figure 18.- Concluded.



(a) Right-wing tip.

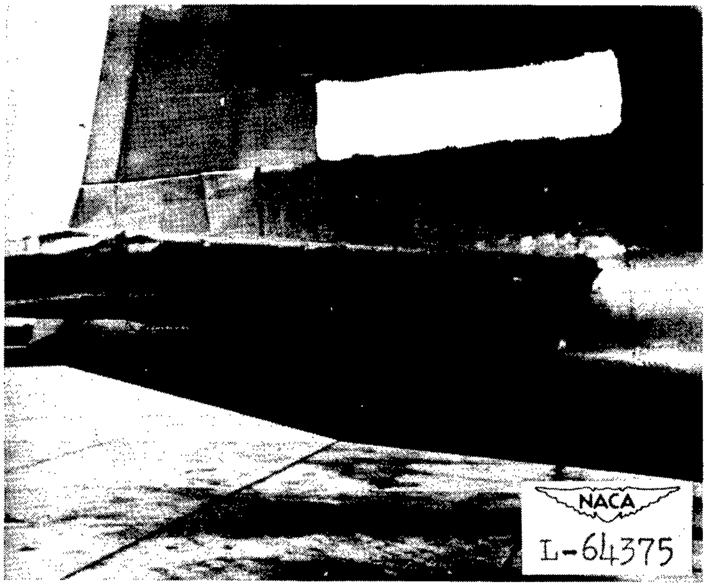
L-64363



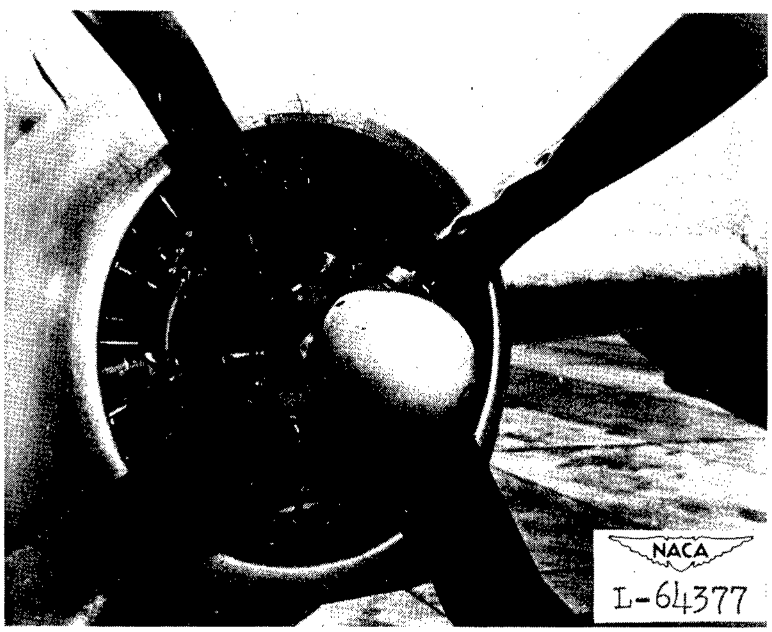
(b) Right-horizontal-stabilizer tip.

L-64362

Figure 19.- Hail case 17. B-29 airplane. (Time in hail unknown; TAS 220 mph.)

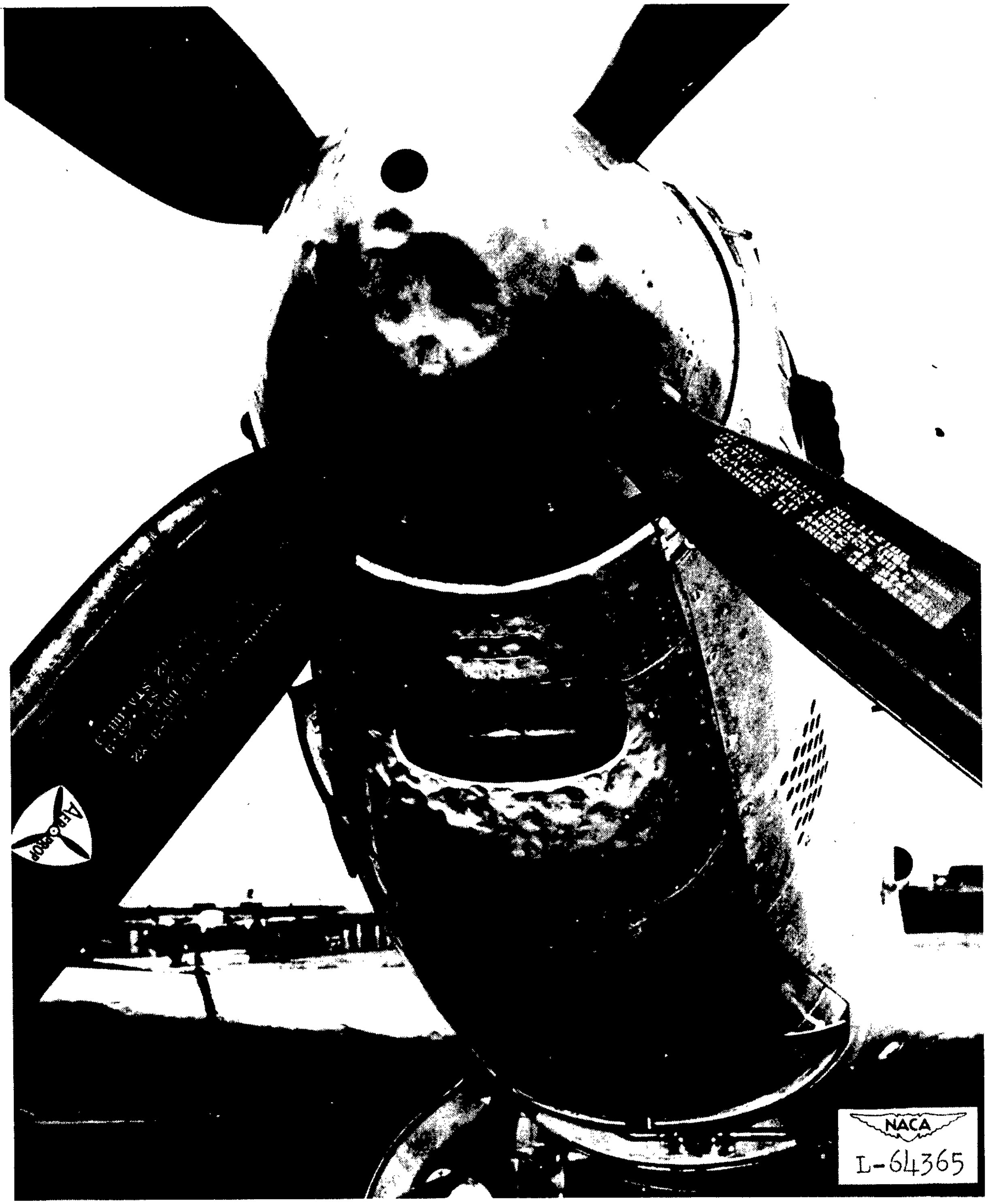


(a) Right-horizontal-stabilizer tip.



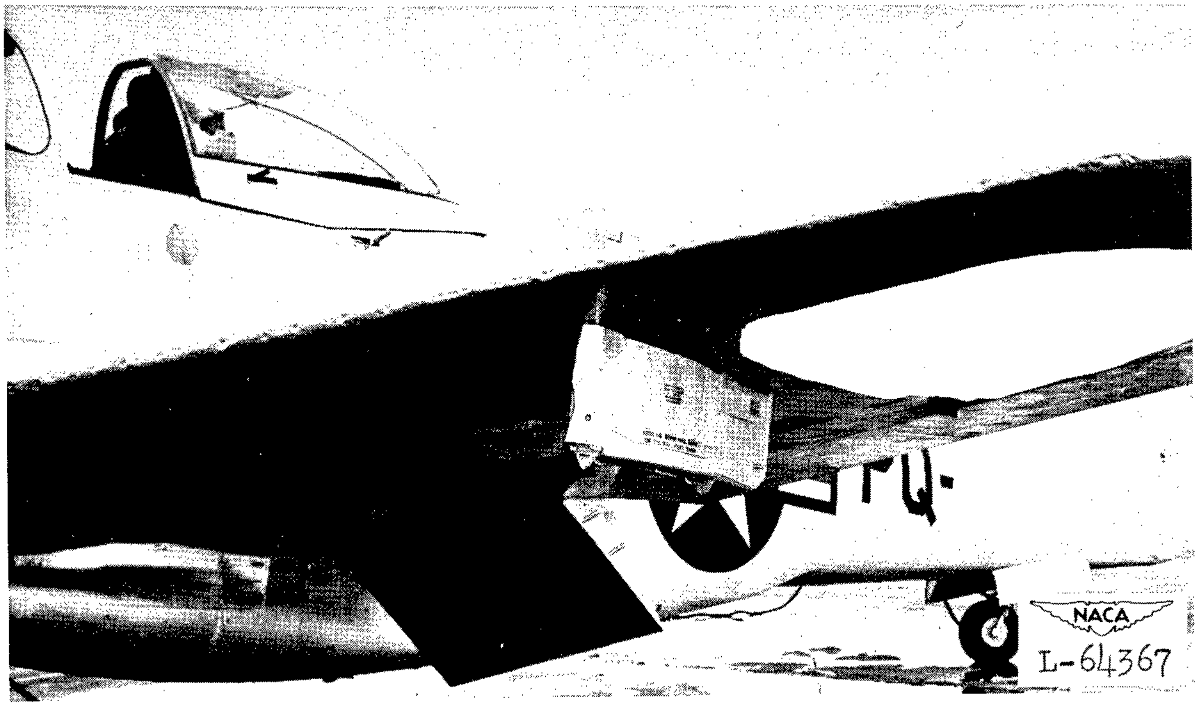
(b) Spinner and propeller cuff. Engine 2.

Figure 20.- Hail case 19. B-29 airplane. (Time in hail 20 sec; TAS 265 mph.)

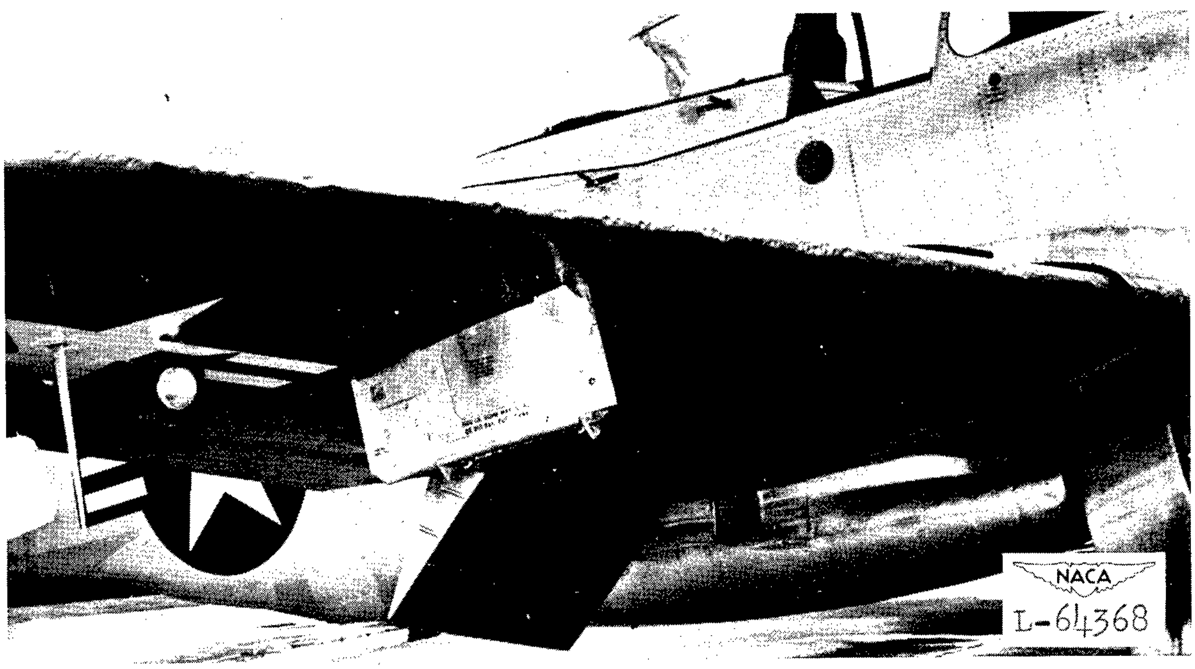


(a) Spinner and air scoop.

Figure 21.- Hail case 22. F-82 airplane. (Time in hail 30 sec; TAS 305 mph.)

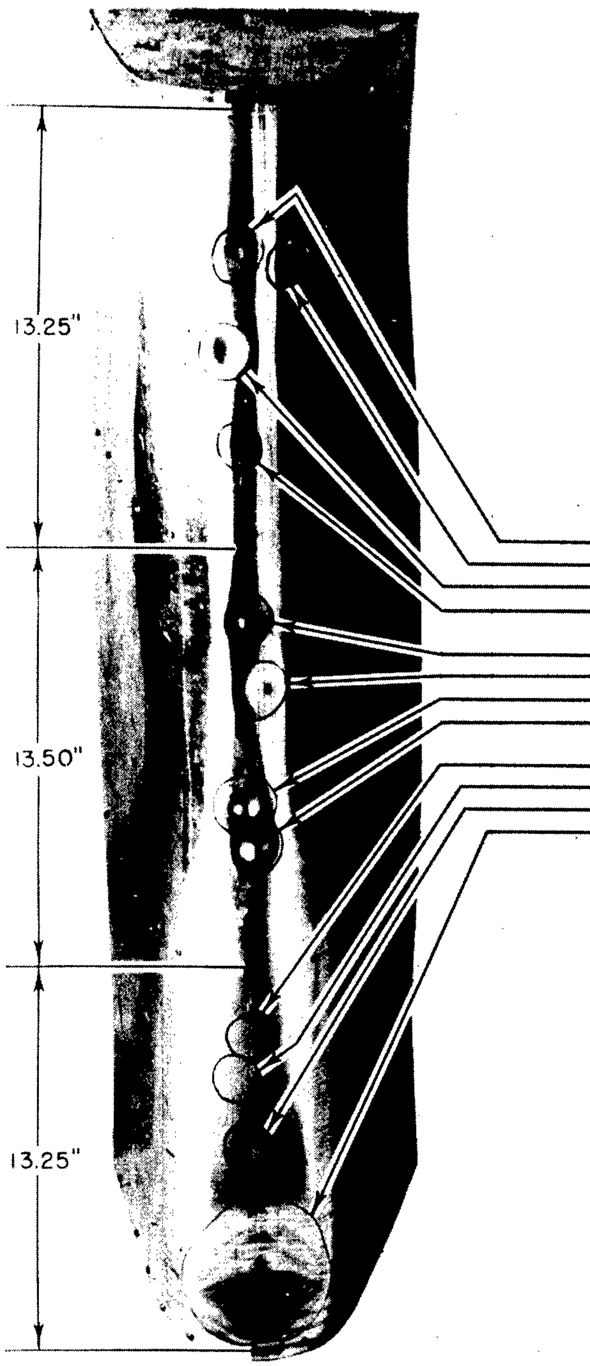


(b) Leading edge of left wing and bomb rack.



(c) Leading edge of right wing and bomb rack.

Figure 21.- Concluded.



TEST SPECIMEN NUMBER 1
0.040 INCH 75S-T ALUMINUM

TEST NO.	ICE SPHERE DIAMETER inches	ICE SPHERE WEIGHT grams	VELOCITY mph	INDEN-TATION[1] inches
583D	0.75	2.3	345	0.037
C	"	2.3	375	0.012[2]
E	"	2.5	460	0.130
B	"	2.3	290	0.010
A	"	2.1	300	None
I	"	2.2	455	0.075
F	"	2.1	430	0.057
G	"	2.5	— [3]	.130
H	"	2.5	— [4]	.150
586 A	1.25	14.5	110	0.000
B	"	14.7	212	0.010
C	"	14.0	285	0.068
D	"	14.0	395	0.766[5]

NOTE: 1. MEASURED FROM 6 INCH LONG BASE LINE
2. ANGLE OF IMPACT 60 DEGREES
3. APPROXIMATE VELOCITY 460 TO 475 MPH
4. " " " " " "
5. TOTAL INDENTATION MEASURED FROM STRAIGHT LINE BETWEEN STIFFENERS

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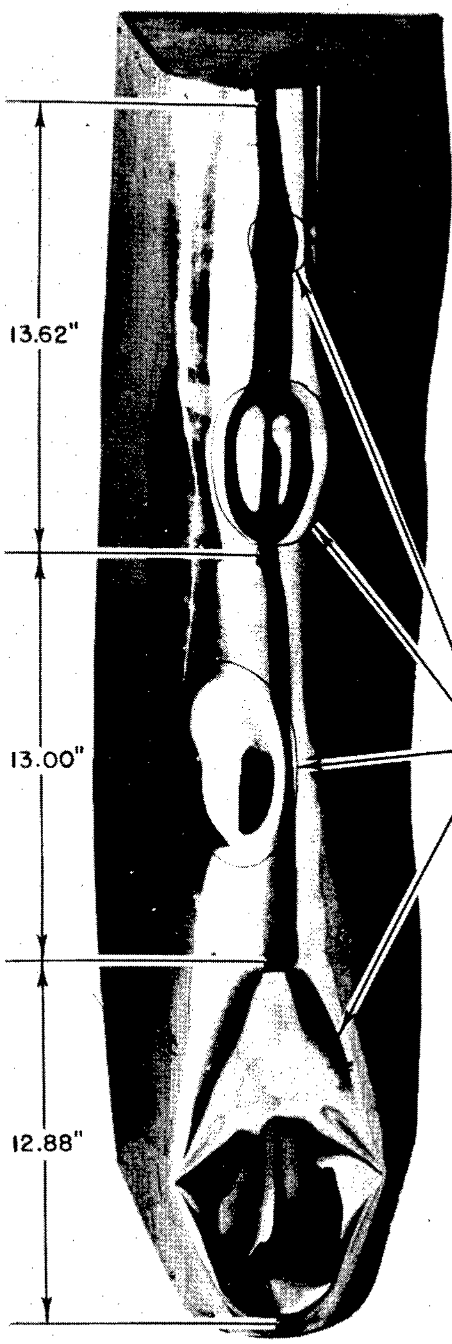
L-74364

(a) For 0.75- and 1.25-inch-diameter ice spheres.

Figure 22.- Results of the impact tests on 0.040-inch 75S-T aluminum (DC-6) wing section. (From reference 40.)



TEST SPECIMEN NUMBER 2
0.040 INCH 75S-T ALUMINUM

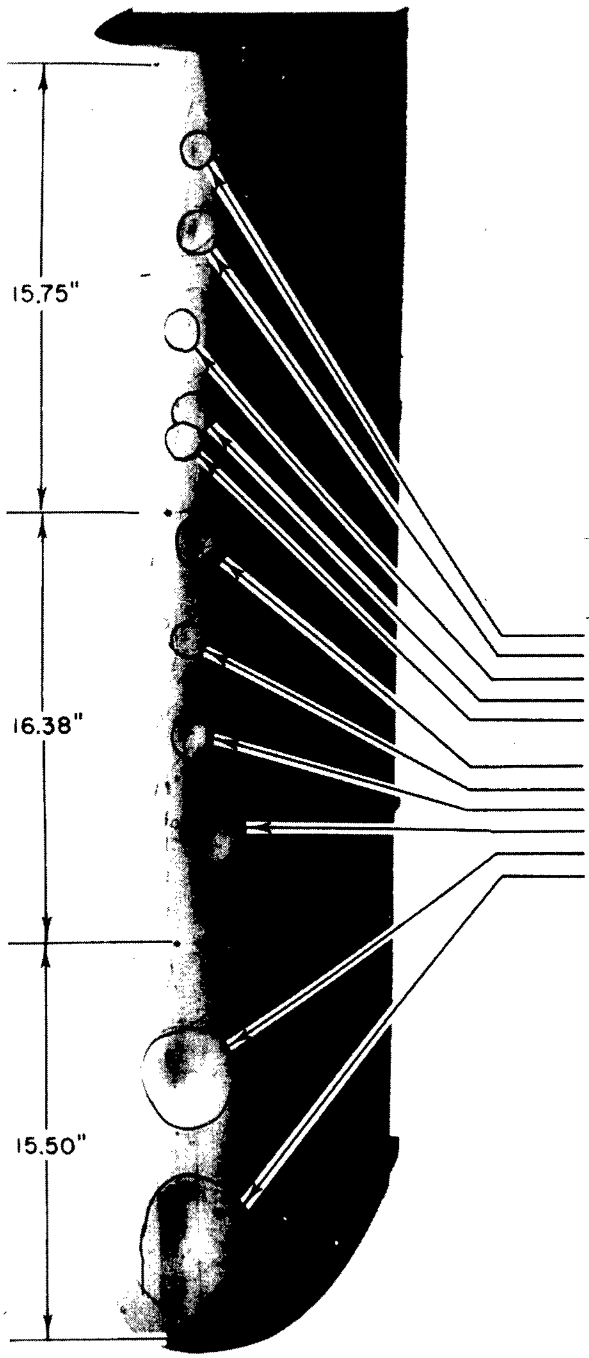
TEST NO.	ICE SPHERE DIAMETER inches	ICE SPHERE WEIGHT grams	VELOCITY mph	INDENTATION[1] inches
588 A	1.88	49.5	177	0.050
B	"	42.5	264	0.432
C	"	46.5	318	0.520
D	"	43.3	378	2.000[2]

NOTE: 1. MEASURED FROM 6 INCH LONG BASE LINE
2. MEASURED FROM STRAIGHT LINE BETWEEN STIFFENERS

NACA
L-74365

(b) For 1.88-inch-diameter ice spheres.

Figure 22.- Concluded.



TEST SPECIMEN NUMBER 4
0.045 INCH 24S-T ALUMINUM

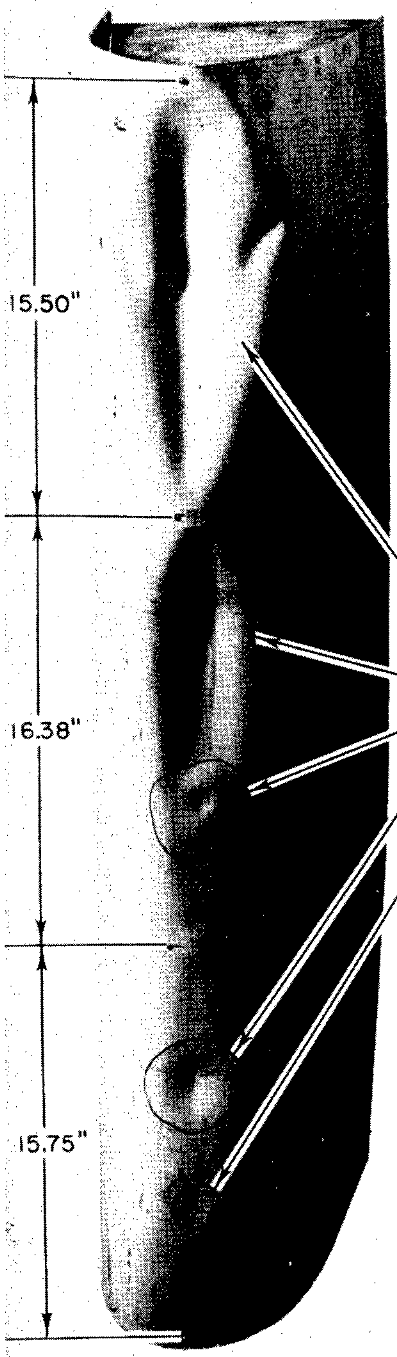
TEST NO.	ICE SPHERE DIAMETER inches	ICE SPHERE WEIGHT grams	VELOCITY mph	INDENTATION[1] inches
584 D	0.75	2.0	300	0.050[3]
C	"	2.1	280[2]	0.080
B	"	2.3	258	0.060
A	"	2.2	206	0.017
E	"	2.0	390	—[4]
585 A	1.25	14.1	156	0.096
B	"	14.4	123	0.030
C	"	14.3	194	0.102
D	"	14.0	280	0.265
E	"	13.8	380	0.413
F	"	13.8	415	0.800

NOTE: 1. MEASURED FROM 6 INCH LONG BASE LINE
2. APPROXIMATED FROM AIR PRESSURE-VELOCITY CURVE
3. QUESTIONABLE VALUE
4. ICE BALL BROKEN BEFORE IMPACT

NACA
L-74366

(a) For 0.75- and 1.25-inch-diameter ice spheres.

Figure 23.- Results of the impact tests on 0.045-inch 24S-T aluminum (DC-3) wing section. (From reference 40.)



TEST SPECIMEN NUMBER 3
0.045 INCH 24S-T ALUMINUM

TEST NO.	ICE SPHERE DIAMETER inches	ICE SPHERE WEIGHT grams	VELOCITY mph	INDENTATION[1] inches
587 E	1.88	44.1	370	1.859
D	"	47.1	294	1.015
C	"	48.0	248	—[2]
B	"	42.0	187	0.261[3]
A	"	47.1	114	0.074

NOTE: 1. MEASURED FROM 6 INCH LONG BASE LINE
2. SUBSEQUENT IMPACT CHANGED SHAPE OF ORIGINAL INDENTATION
3. MEASURED FROM STRAIGHT LINE BETWEEN STIFFENERS

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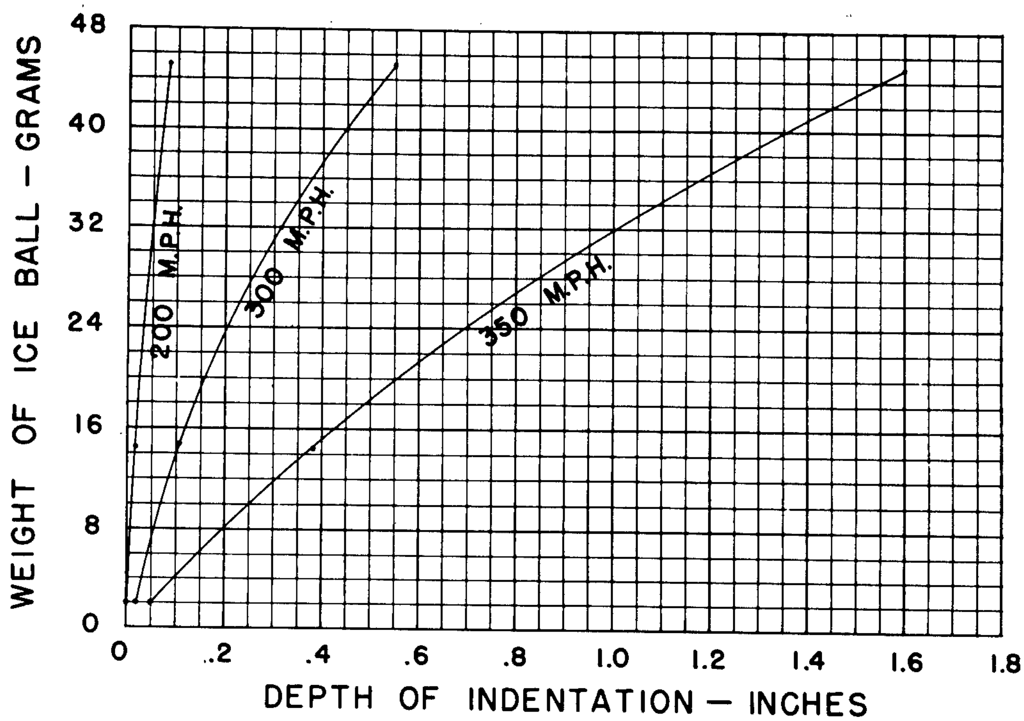
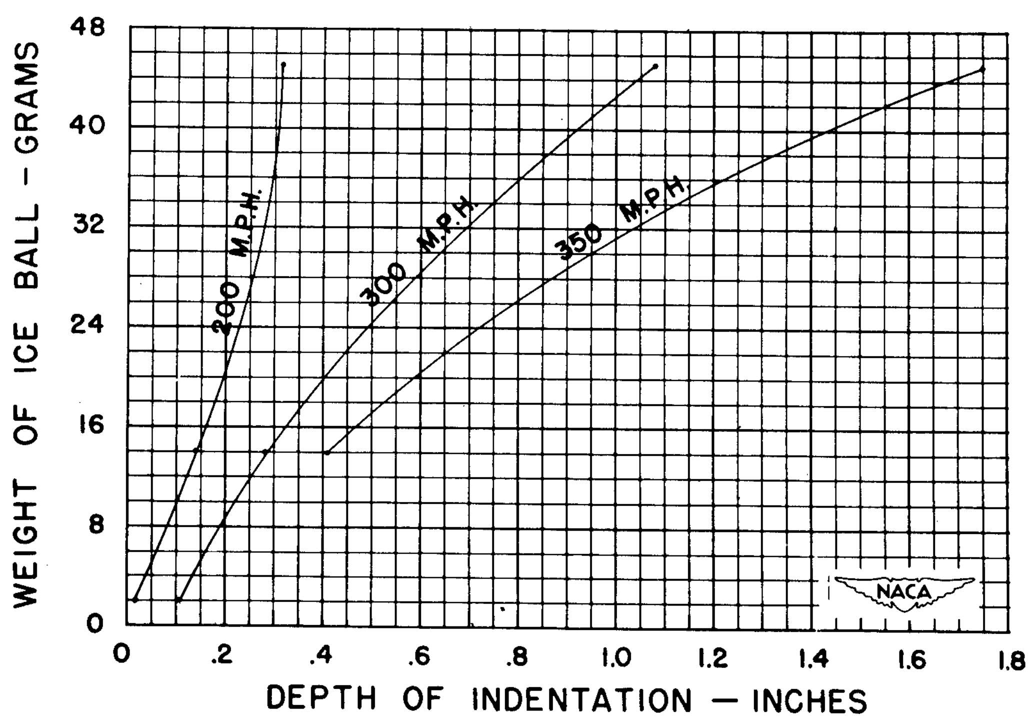
L-74367

(b) For 1.88-inch-diameter ice spheres.

Figure 23.- Concluded.

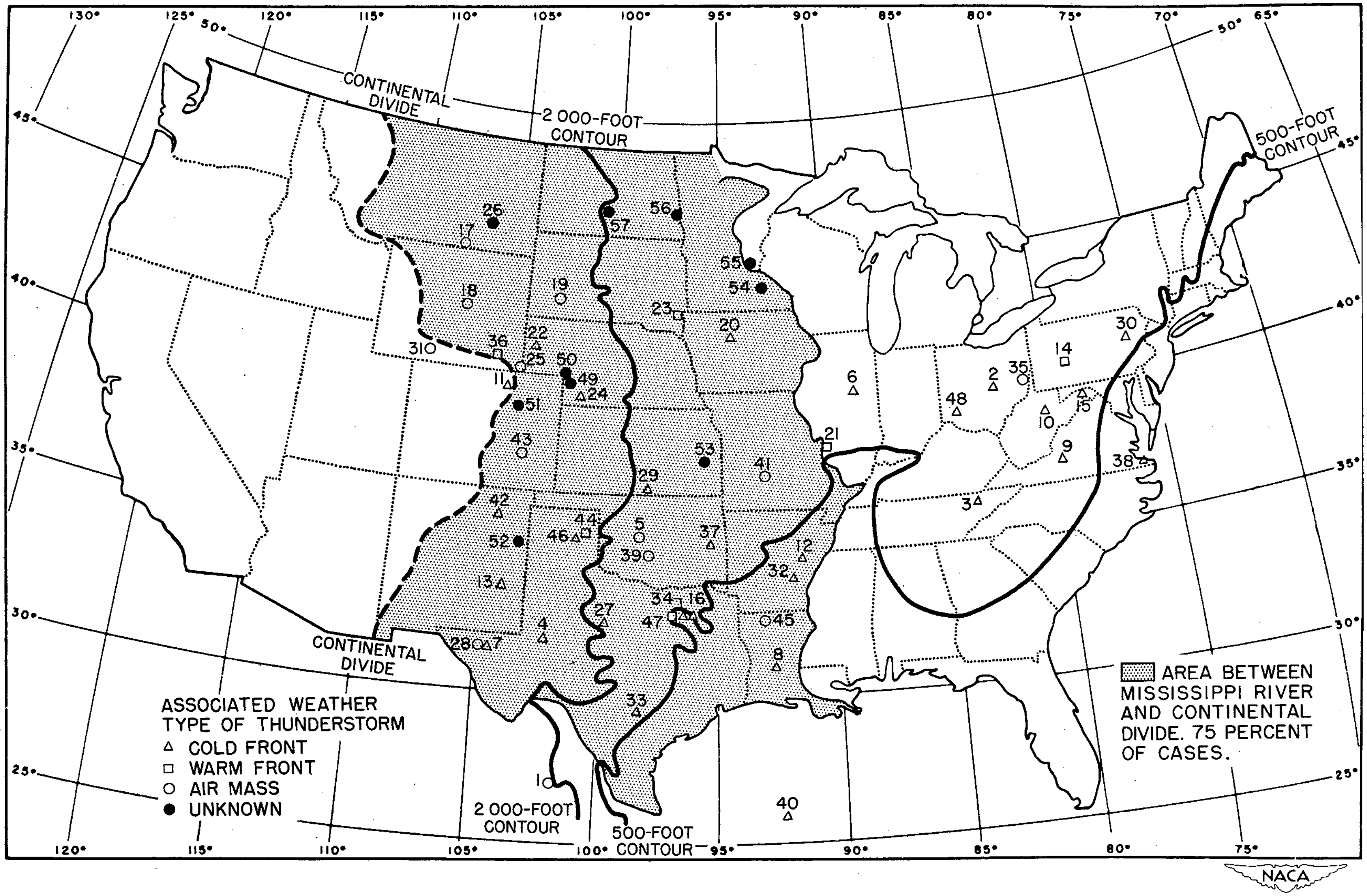


(a) 0.040-inch 75S-T aluminum. DC-6 airplane.



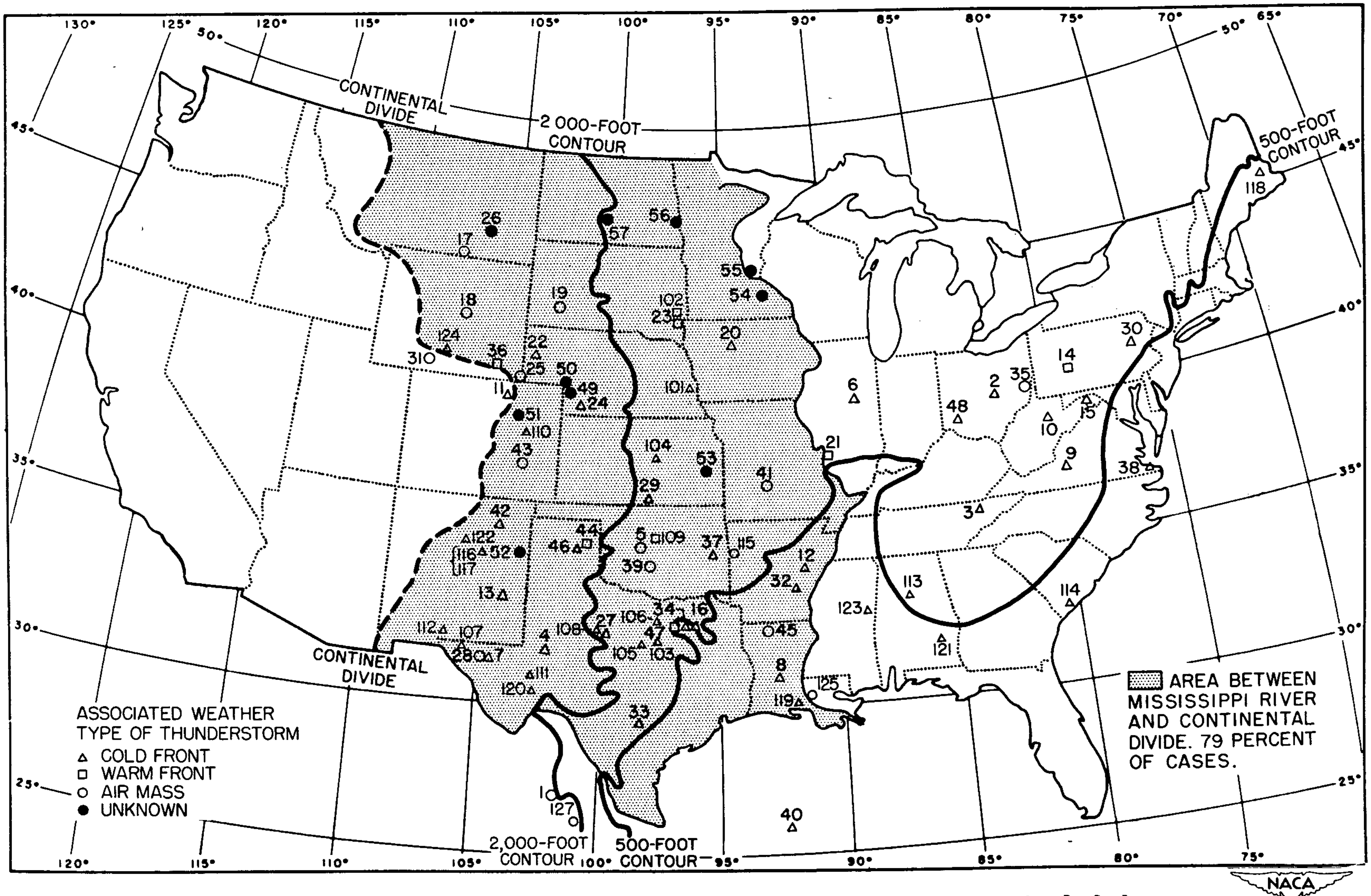
(b) 0.045-inch 24S-T aluminum. DC-3 airplane.

Figure 24.- Effect of impact velocity on the extent of hail damage to aluminum wing sections. (From reference 40.)



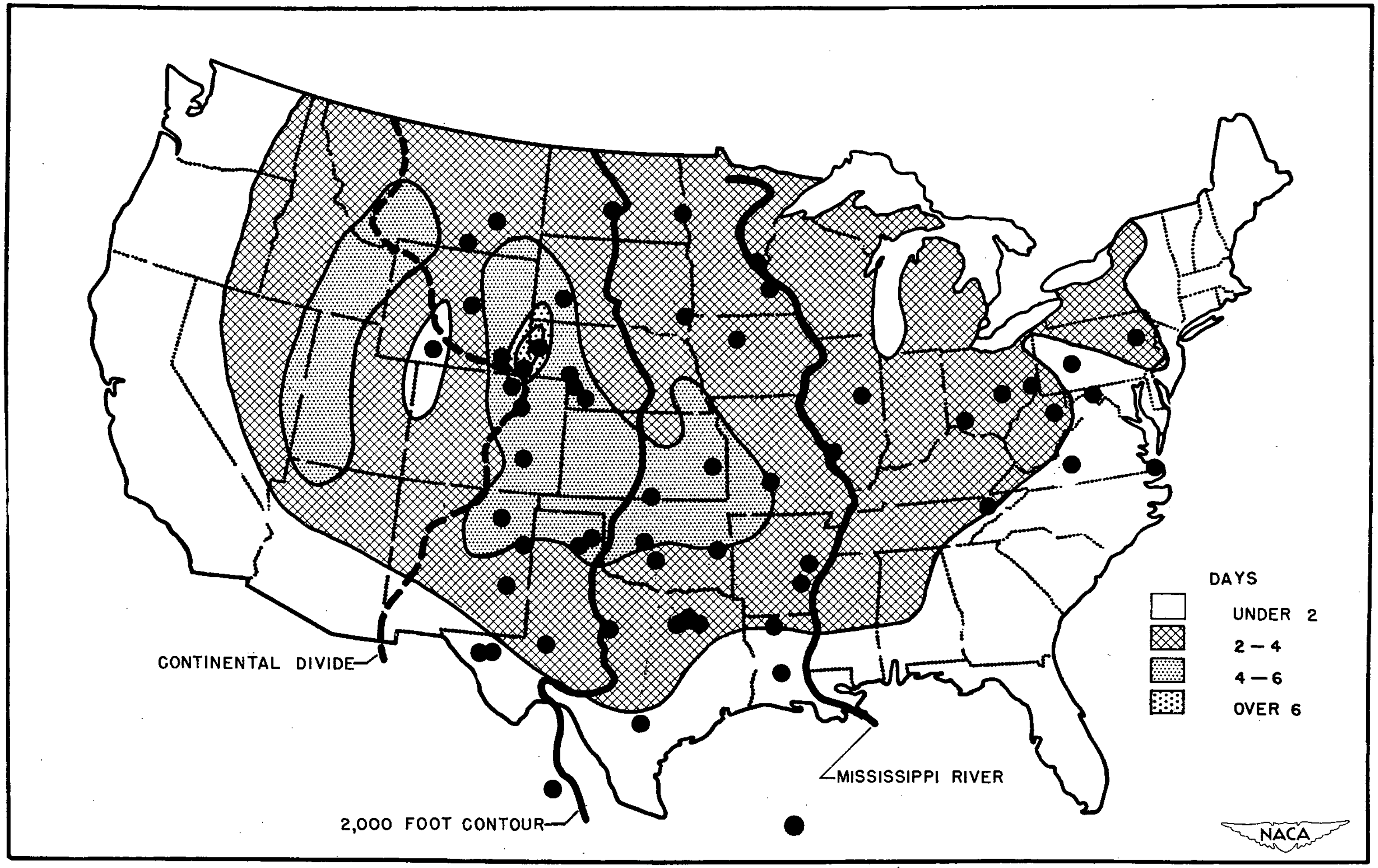
(a) Location of 57 cases. (Number of each location indicates case number from tables II to IV.)

Figure 25.- Location where hail damaged airplanes in flight.



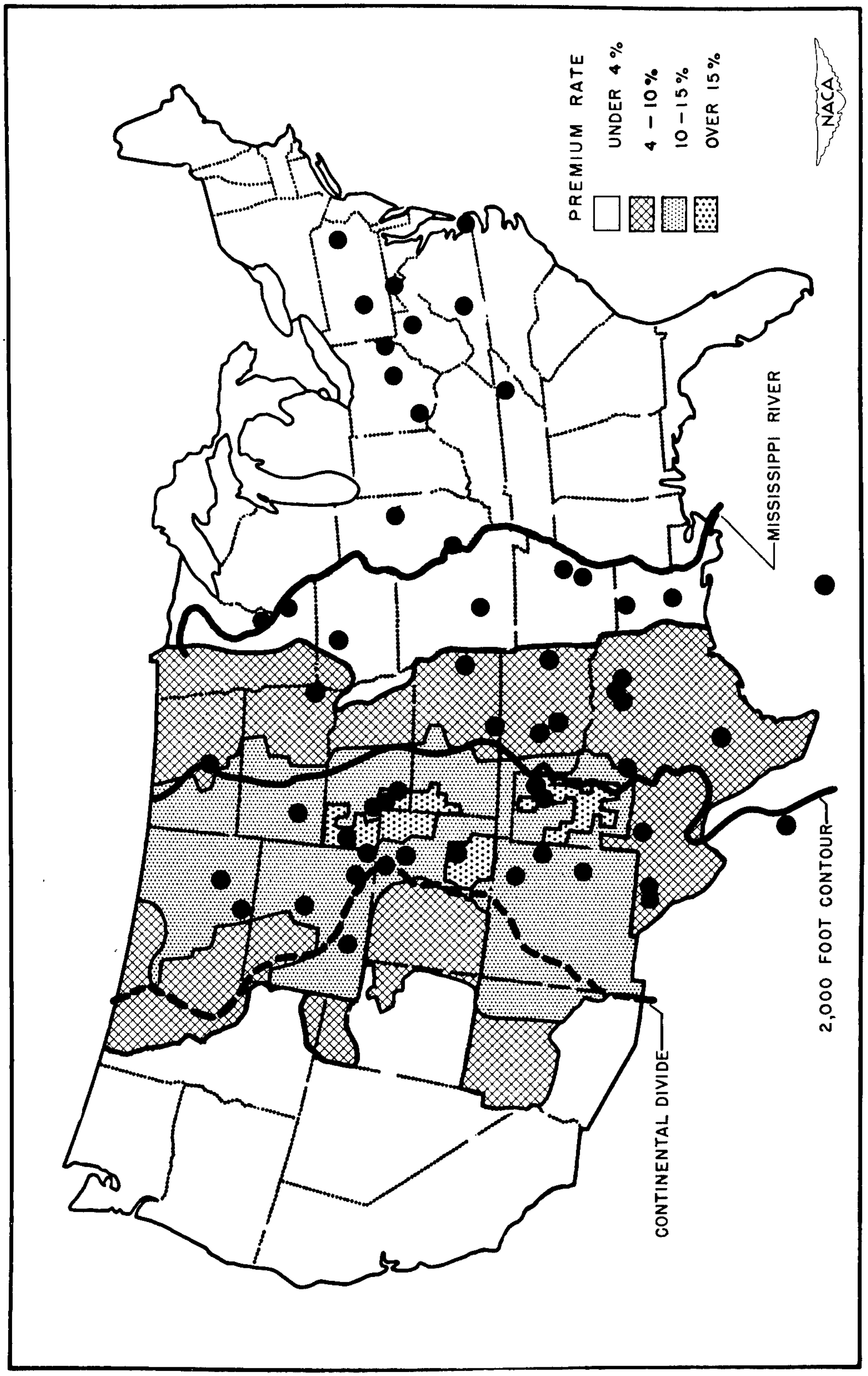
(b) Location of 83 cases. (These cases include the 57 accidents included in fig. 25(a) plus 26 additional cases added after completion of the analysis.)

Figure 25.- Concluded.



(a) Chart of average number of days with hail. (Adapted from figs. 3(a) and 25.)

Figure 26.- Distribution of 57 cases where hail damaged airplanes superimposed on charts showing annual distributions of hail and crop-hail insurance rates.



(b) Chart of crop-hail premium rates. (Adapted from figs. 4 and 25.)

Figure 26.- Concluded.

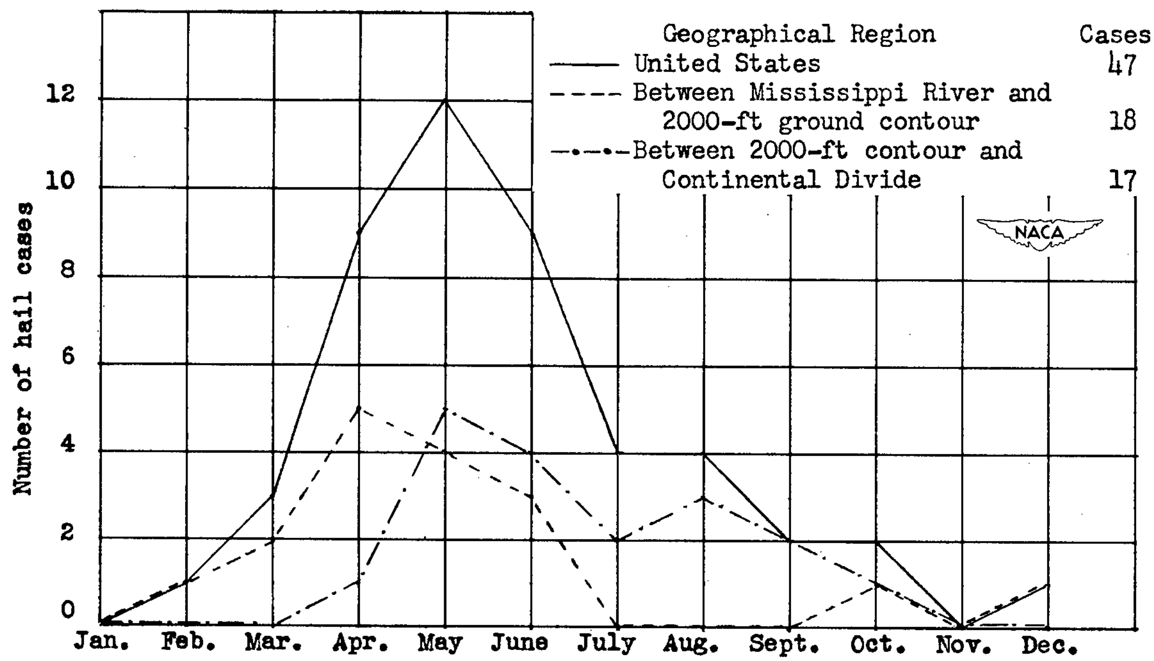


Figure 27.- Monthly distribution of hail damage to 47 aircraft with respect to geographical location in the United States.

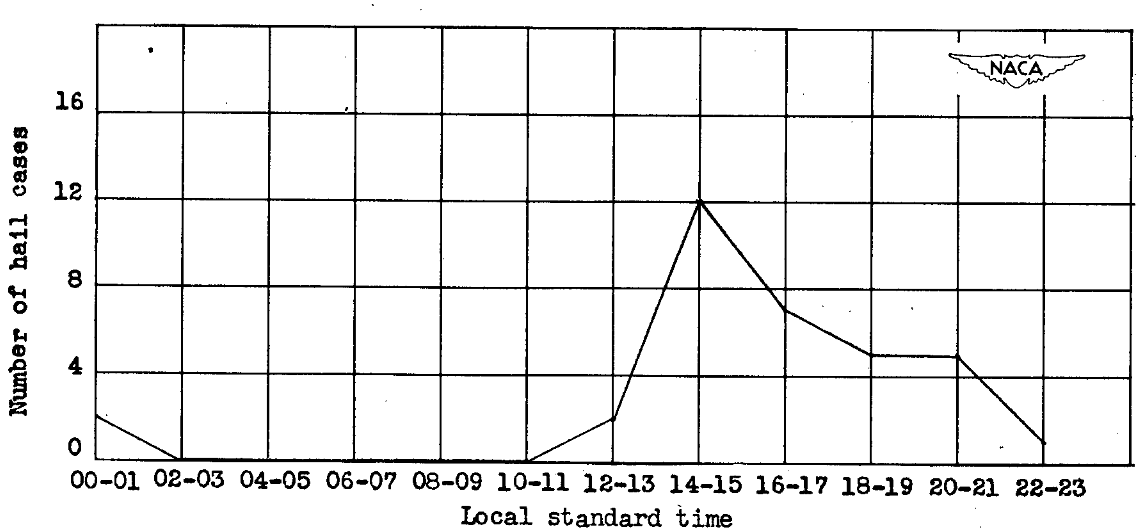


Figure 28.- Hourly distribution of hail damage to 34 aircraft over the United States.

Figure 29.- Hail-catcher installation on American Airlines Convair (Flagship Gamma). (From reference 44.)

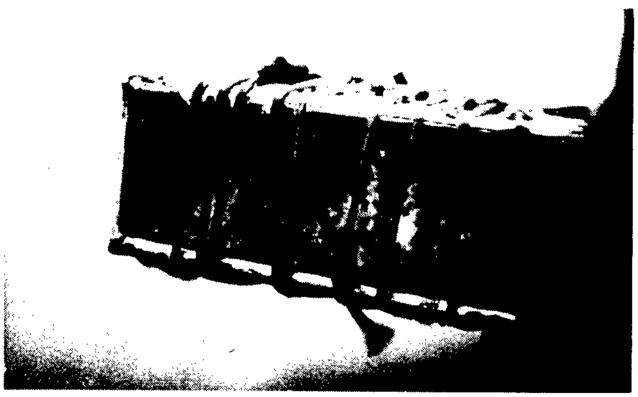
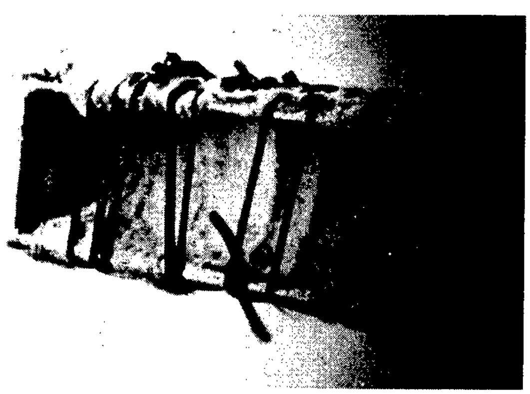


Figure 30.- Small hail or graupel in the hail catcher obtained while flying through a thunderstorm at temperature just above freezing, 4° C. (The graupel observed on the surface did not damage subsequent hailstones that entered the cotton.) (From reference 44.)



NACA
L-74368

Figure 31.- Thin layer of packed ice in the hail catcher from snow particles, slush, and soft hail obtained while flying through a thunderstorm at temperature just below freezing, 0° to -5° C. (From reference 44.)

B I B L I O G R A P H Y

The pages that follow include a comprehensive list of articles concerning information on hail and hail formation. This compilation was made by the authors through sources made available to them in contacts with the Blue Hill Observatory, the American Meteorological Society, the Evans Electronic Laboratory, and others.

Many of these documents were not available to the National Advisory Committee for Aeronautics so that accuracy of the citations could not be ascertained. Those articles which are available to the NACA and for which the citations have been checked against the sources are indicated in the lists by the use of an asterisk preceding the citation.

For the convenience of the reader, this bibliography is divided into sections according to subject matter and in chronological sequence as follows:

In addition, brief abstracts are included after the citations, when this information was accessible, as well as a notation of the source of availability.

The following bibliographies on hail are available for supplementary hail literature to the NACA Bibliography: (Bibliography (1) includes approximately 580 articles of old, foreign literature which is not included in the NACA Bibliography. Bibliography (4) includes about 80 articles of more recent foreign literature which has not been included here.)

(1) 1889: U.S. Signal Office. Bibliography of Meteorology, Part II, Moisture. Washington, 1889, pp. 316-366. 701 items; 122 in English. Covers period from beginning of printing to 1881, supplement continues to close of 1887.

(2) 1937: U.S. Works Progress Administration (Hail Section of Card Catalogue on Meteorology). Compiled from material in 16 periodicals of U.S. (14) and Great Britain (2). Available at the U.S. Weather Bureau in Washington, D. C., and at Blue Hill Observatory in Boston, Mass.

(3) 1949: Meteorological Office Library of Great Britain (Subject Catalogue, Section on Hail). Material included for years 1900 to 1949. (Microfilm available).

(4) 1950: American Meteorological Society, Meteorological Bibliographies and Abstracts, Vol. 1, No. 4, April 1950. Approximately 240 items listed.

A.- HAIL IN GENERAL

1850 - 1899

A-1. Anon.: Hail. Scientific American (New York), vol. 5, Feb. 9, 1850, p. 168.

A-2. Tyndall, John: Remarks on Foam and Hail. Phil. Mag. (London), vol. 13, 1857, pp. 352-353.

A-3. Tomlinson, Charles: The Frozen Stream. An Account of the Formation and Properties of Ice in Various Parts of the World. 16mo., London, 1862, 260 pp.

A-4. Saint-Hilaire, J. Barthelemy: Météoroligie d'Aristote traduite en francais. Paris, 1863.

A-5. Oliver, J. A. W.: The Observation of Hailstorms. Nature (London), vol. 24, 1881, pp. 189-190. Also entitled "Note on the Formation of Hail." Quarterly Jour. Roy. Meteorol. Soc., New ser., vol. 7, no. 40, Oct. 1881, pp. 247-249. Lists 13 items which should be recorded by observers.

A-6. Anon.: Tornadoes, Whirlwinds, Waterspouts and Hailstones. Nature (London), vol. 25, 1881-1882, pp. 155-157, and 291-292.

A-7. Russell, Rollo: On Hail. Edward Stanford, publ. (London), 1893, 224 pp.; summary in Quarterly Jour. Roy. Meteorol. Soc., vol. 19, Oct. 1893, pp. 258-260. 2 photos., references. Descriptions given of hailstorms all over the world; various theories of hail summarized; development of a hailstorm traced; and the author's conclusions.

*A-8. Davis, W. M.: Elementary Meteorology. Ginn & Co. (Boston), 1894, pp. 248-295. Discusses thunderstorms, cyclones, tornadoes, aurora, waterspouts, thunder, lightning, atmospheric electricity, snow, hail, ice storm, cause and distribution of rainfall, relation of rainfall and agriculture, relation of rainfall and forests, and artificial rain.

A-9. Abbe, Cleveland, ed.: Hail and a Rain Gauge for Its Measurement. Monthly Weather Rev., vol. 25, no. 5, May 1897, pp. 210-211. Reported from Beaver, Okla.

1900 - 1929

A-10. Hann, Julius von: Lehrbuch der Meterologie. Hagelwetter. Third ed., Chr. Herm. Tauchnitz, Auflage (Leipzig), 1915, pp. 708-725. (Available Lib. of Congress) 2 figures, 2 plates, 1 table. Comprehensive summary of knowledge on hail, hail structure, hail frequency, hail formation, and hail occurrence up to the date of publication of this edition.

A-11. Brooks, Charles F.: Hail. Science (Washington), New ser., vol. 44, Sept. 8, 1916, pp. 356-357.

A-12. Talman, Charles Fitzhugh: Hail and Its Half-Brothers. Nature Mag. (Washington), vol. 4, no. 4, Oct. 1924, pp. 197-202. Photos. Popular article dealing with characteristics of true hail, famous hailstorms, types of crops damaged, and methods of prevention.

A-13. Ward, Robert DeCourcy: The Climates of the United States. Ginn & Co. (Boston), 1925, pp. 335-338. 1 figure. Points out certain characteristics of hail, occurrence with thunderstorms, narrow area over which it falls, and prevalence in the spring. Reference to hail damage. Figure shows annual number of days with hail during the frostless season.

A-14. Brooks, Charles F.: Cold-Front Hail. Bull. Am. Meteorol. Soc., vol. 10, no. 10, Oct. 1929, p. 186.

1930 - 1939

*A-15. Shaw, Sir Napier: Manual of Meteorology. Cambridge Univ. Press (London), vol. III, 1930, pp. 336-339. Relates three accounts of the fall of unusually large hailstones, and concludes that large hailstones are possibly formed when the force of the electric field in thunderstorms is strong enough to equalize the force of gravity.

A-16. Schmauss, A.: Ist Hagel Kosmiches Eis? (Is Hail Cosmic Ice?) Zeitschr. fur die Gesamte Naturwissenschaft (Brunswick), Bd. 3, 1937, pp. 233-238. (Available Lib. of Congress.)

A-17. Aujeszky, Laszlo: A "tiszta jégeső" kérdése. (The Problem of "Pure Hail.") Időjarás (Budapest), vol. 24, no. 14, Nov.-Dec. 1938, pp. 233-242; summary in German, pp. 264-265. (Available Lib. of Congress.) Equations. Definition of "pure hail" which is claimed to be more destructive than when found with other forms of precipitation, damage from pure hail.

A-18. Obolensky, V. N.: Meteorology. Hydrometeorological Publishing Office (Leningrad), 1938, pp. 794-795. English translation by U. S. Air Force Headquarters is available.

A-19. Puppo, A.: La Grandine. (Estratto dalla reccolta delle conferenze della II Parte del "Corso per la rilevazione estima dei danni della grandine" tenuto a Balogna a cura della Commissione Intersindacale Periti Grandine nell Aprile 1938). Tipografia, Editrice Sallustiana (Roma), 1938, 23 pp.

A-20. Kolobkov, N. V.: Grozy i shkvaly. (Thunderstorms and Squalls). Gidromet. Izdat. (Moscow), 1939, pp. 58-67. (Available Lib. of Congress. Translation by Alexander G. Alexeeff is available at Am. Meteorol. Soc. Abstracts, Washington.) 2 figures. First part deals with general information: accounts of hailstorms, problem of hail formation, and appearance of hailstone. Second part deals with hail distribution in Russia.

1940 - 1950

*A-21. Lansberg, Helmut: Physical Climatology. Gray Printing Co. (Du Bois, Pa.), 1943, pp. 183-185. Quite general discussion on hail formation, size, and distribution.

*A-22. Petterssen, Sverre: Introduction to Meteorology. McGraw-Hill Book Co., Inc. (New York), 1941, pp. 37 and 97. Definition of hail, and brief description of formation.

A-23. Suring, Reinhard: Die Wolken. Bd. 16 of Problele der Kosmischen Physik, Christian Jensen, ed., Akademische Verlagsges (Leipzig), 1941, p. 110.

*A-24. Anon.: Hail. Tech. Note No. 52-43, Bur. Aero., Navy Dept. (Washington), July 7, 1943, 7 pp., 7 figures. Contains definition of hail, theory of hail formation, frequency of occurrence in relation to thunderstorms, difficulties in forecasting, dangers of hail in flight, precautions to pilot and meteorologist.

A-25. Morandi, Luis: Actividades meteorológicas en el Uruguay; una investigación metódica de la frequencia e intensidad del granizo en el Uruguay. (A methodical investigation of the frequency and intensity of hail in Uruguay.) Revista Meteorológica (Montevideo), Año 3, no. 11, July 1944, pp. 297-298. (Available U. S. Weather Bur. Lib.) Describes project to begin in January 1945 whereby persons untrained in meteorology will take hail observations throughout the country.

*A-26. Hewson, E. Wendell, and Longley, Richmond W.: Meteorology Theoretical and Applied. John Wiley & Sons, Inc. (New York), 1944, pp. 319-320, 375-376. Presents very brief information on formation and distribution.

*A-27. Anon.: Hail. Encyclopedia Britannica, 13th Ed., vol. 11, 1945, pp. 76-77. Very general information on hail.

*A-28. Anon.: Handbook of Meteorology. Edited by Berry, F. A., Jr., Bollay, E., and Beers, Norman R. McGraw-Hill Book Co., Inc. (New York), 1945, pp. 257-258, 261-262, 359-361, 712. Presents brief references to hail formation; hail as a form of precipitation from cumulus-type clouds; equation for hail stage of saturated air; data on hailstone size distribution.

A-29. Lane, Frank Walker: The Elements Rage. Hail. London Country Life, Ltd., 1945, pp. 49-58. (Available Lib. of Congress.) Article in popular style covering formation of hailstones, record size hailstones, severe hailstorms, loss of property and human life, and mechanical methods of warding off hailstorms.

*A-30. Anon.: WBAN Manual of Surface Observations. Circular N. Sixth ed., U. S. Weather Bur. (Washington), Jan. 1949, p. 22. Official U. S. definitions of hail and small hail.

*A-31.- Anon.: Survey of Hail Studies. Hdqrs., Air Weather Service (Washington), Feb. 1949, 27 pp., 5 tables, 32 references. Report deals with: (a) conditions which are known or appear to be present whenever hail occurs, (b) formation and growth of hail, and (c) data available as to size, frequency, and distribution of hail. Reviews briefly most recent work on theories of hail formation and problems facing meteorologists and forecasters.

A-32. Escobar, V., Ismael: Estudio sobre el granizo. (Study on Hail.) Nimbus, La Paz (Bolivia), Año 1, no. 3, July-Sept. 1949, pp. 1-32; no. 4, Oct.-Dec. 1949, pp. 14-29. Several figures and tables. Specific information on hail in Bolivia. One table shows monthly hailstorms for 121 stations over periods varying from 2 to 30 years. Another table gives seasonal distribution. Also includes a general discussion of hail formation, structure, and damage.

B.- HAIL STRUCTURE

PREVIOUS TO 1850

B-1. Fairfax, Nathaniel: Account of Hailstones of an Unusual Bigness, with His Reflections on Them. Phil. Trans. (London), vol. 2, 1667, pp. 481-482.

B-2. Hooke, Robert: Philosophical Experiments. Account of the Great Hailstones That Fell in London on May 18, 1680. W. Derham, Publ., 12mo. (London), 1762, pp. 49-53.

*B-3. Clark, Daniel A.: On Some Curious and Singular Appearances of Snow and Hail. Am. Jour. Sci. (New Haven), First ser., vol. II, 1820, pp. 132-134. (Available U. S. Weather Bur. Lib.)

B-4. Waller, Augustus: On Hail and on the Organic Bodies Contained in Hailstones, etc. Phil. Mag. (London), vol. 30, 1847, pp. 159-171.

B-5. Anon.: Singular Fall of Ice. Scientific American (New York), vol. 4, Sept. 8, 1849.

1850 - 1899

B-6. Sutcliffe, Thomas: Notice of Remarkable Hailstones Which Fell at Headingly near Leeds, on the 7 May 1862. Proc. Roy. Soc. (London), vol. 12, 1862-1863, pp. 239-242. Also in Phil. Mag. (London), vol. 26, 1863, p. 67.

B-7. Lowe, E. J.: Snow-Crystals and Hail, as Observed at the Beeston Observatory. Proc. British Meteorol. Soc. (London), vol. 2, 1863-1865, pp. 105-107.

B-8. Anon.: Hail and Hailstorms. Scientific American (New York), Second ser., vol. 21, July 10, 1869, p. 26.

B-9. Anon.: Nocturnal Hailstorms - Hailstones of Singular Form. Scientific American (New York), Second ser., vol. 21, July 31, 1869, p. 72.

B-10. Procter, H. R.: The Structure of Hailstones. Nature (London), vol. 3, 1870-1871, p. 128.

B-11. Kenngott: Hailstones of Salt and Sulphide of Iron. Am. Jour. Sci. (New Haven), Third ser., vol. 3, 1872, p. 239.

B-12. Bonavia, E.: Hailstones in India. Nature (London), vol. 15, 1876-1877, p. 538.

B-13. Rainey, H. J.: Note on Certain Peculiarities Observed in Hailstones Which Fell at Khulna, Jessore, on the 31st March 1878. Proc. Asiatic Soc. Bengal (Calcutta), 1878, pp. 125-126.

B-14. Blanford, H. F.: Note to Accompany Some Drawings of Large Hailstones by Col. H. H. Godwin-Austin and S. E. Peal. Proc. Asiatic Soc. Bengal (Calcutta), 1880, pp. 103-104.

B-15. Calvert, Frank: Shower of Angular Hailstones. Scientific American (New York), Second ser., vol. 43, 1880, p. 373.

B-16. Ward, M. F.: Remarkable Hailstones. Symons's Meteorol. Mag. (London), vol. 15, 1880, pp. 133-136; vol. 16, 1881, pp. 138-139.

B-17. Anon.: Hail-Stones of Unusual Size. Monthly Weather Rev., vol. 10, no. 5, May 1882, p. 15; vol. 10, no. 6, June 1882, p. 14; vol. 11, no. 5, May 1883, pp. 112-113; vol. 11, no. 7, July 1883, pp. 158-159; vol. 12, no. 7, July 1884, pp. 168-169.

B-18. Elwood, Martin: An Eighty Pound Hailstone. Scientific American (New York), Second ser., vol. 47, August 19, 1882, p. 119. Extract from Salina, Kansas, Journal.

B-19. Schwedoff, Theodore: Red Hail. Nature (London), vol. 32, 1885, p. 437.

B-20. Middlemiss, C. S., and Johnstone, Alexander: Top-Shaped Hailstones. Nature (London), vol. 35, 1886-1887, pp. 413-414, and p. 536.

B-21. Anon.: Remarkable Hailstones. Nature (London), vol. 36, 1887, pp. 44-45.

B-22. Bowrey, J. J.: Fall of Peculiar Hailstones in Kingston, Jamaica. Nature (London), vol. 36, 1887, pp. 153-154.

B-23. Anon.: Microbes in Hailstones. Science (Washington), vol. 16, Aug. 1, 1890, pp. 64-65.

B-24. Huntington, O. W.: Hailstones of Peculiar Form. Am. Jour. Sci. (New Haven), Third ser., vol. 40, 1890, p. 176.

B-25. Abbott, A. C.: Bacteria in Hailstones. Scientific American (New York), Second ser., vol. 67, Sept. 17, 1892, p. 181.

B-26. Minter, Frank: Hailstones of Great Size. Scientific American (New York), Second ser., vol. 74, May 20, 1896, p. 347. Occurred at Corning, Kansas.

B-27. Anon.: Iron Pierced by Hailstone. Scientific American (New York), Second ser., vol. 75, Sept. 12, 1896, p. 223. 1 photo.

B-28. Abbe, Cleveland, ed.: The Structure of Hailstones. Monthly Weather Rev., vol. 25, no. 8, Aug. 1897, pp. 352-353. Description of peculiar hailstones that fell at Hannover, Germany, Jan. 9, 1897.

1900 - 1919

B-29. Abbe, Cleveland, ed.: Structure of Hailstones. Monthly Weather Rev., vol. 33, no. 10, Oct. 1905, p. 445.

B-30. Webster, E. S.: Structure of Hailstones. Monthly Weather Rev., vol. 34, no. 3, March 1906, p. 109.; comments by Cleveland Abbe, ed. Size and shape of hailstones. Abbe gives three possible explanations for origin of snowy ice at center of hailstones.

B-31. Landis, D. S.: The Structure of Hailstones. Monthly Weather Rev., vol. 34, no. 6, June 1906, p. 227. Reprint in Quarterly Jour. Roy. Meteorol. Soc., vol. 33, no. 141, Jan. 1907, pp. 63-65. 3 figures. Study made in Texas. Symmetrical hailstones, prevailing form is oblate spheriod. Detailed description of five, seven, and nine layer types. Concludes that it is incorrect to say that the center of a hailstone is either crystal ice or amorphous ice.

B-32. Smith, Wellington: The Structure of Hailstones. Monthly Weather Rev., vol. 34, no. 6, June 1906, pp. 277-278. 1 figure. All stones observed were dished or hollowed toward center; some had holes. Some gave off bubbles when placed in water.

B-33. Abbe, Cleveland, ed.: Suggestions to Observers of Hailstones. Monthly Weather Rev., vol. 34, no. 6, June 1906, p. 278. Hail structure.

B-34. Bigelow, Frank H.: Studies of the Thermodynamics of the Atmosphere. Building of Hail. Monthly Weather Rev., vol. 34, no. 11, Nov. 1906, pp. 514-515. Detailed description of physical structure of hailstones, diameters, classes as to shape, and order of construction from center outward.

B-35. Cline, Joseph L.: Hailstorm at Corpus Christi, Texas. Monthly Weather Rev., vol. 35, no. 5, May 1907, pp. 218-219. Storm occurred on May 31, 1907. Description of hailstones.

B-36. Weinberg, Boris: On the Conservation of Hailstones and the Investigation of Their Microstructure. Science (Washington), New ser., vol. 32, Aug. 12, 1910, pp. 214-216. Also in Nature (London), vol. 89, June 9, 1910, pp. 427-428. Illustrated description of refrigerating chamber and of the method by which a thin section of a hailstone can be obtained for microscopic examination.

B-37. Brown, W. G.: Explosive Hail. Nature (London), vol. 88, Jan. 11, 1912, p. 350.

B-38. Sullivan, Richard H.: Unusual Hailstorm, Wichita, Kansas, May 24, 1912. Monthly Weather Rev., vol. 40, no. 5, May 1912, p. 739. Reprinted in Quarterly Jour. Roy. Meteorol. Soc., vol. 38, Oct. 1912, p. 302. Sizes and composition of stones.

B-39. Lingle, J. D.: Unusual Hailstone Formation. Monthly Weather Rev., vol. 40, no. 6, June 1912, pp. 968-969. 3 figures. Drawings of hailstones of peculiar structure.

B-40. Lloyd, Francis E.: Structure of Hailstones of Exceptional Form and Size. Trans. Roy. Soc. Canada (Ottawa), ser. 3, vol. 10, Sept. 1916, pp. 47-50. Reprinted in Monthly Weather Rev., vol. 45, no. 8, Aug. 1917, p. 412. Storm occurred at Carmel, Calif. Stones had central core with icicle-like projections.

1920 - 1929

B-41. Flora, S. D.: "Snowball" Hail at Topeka, Kansas, March 3, 1920. Monthly Weather Rev., vol. 48, no. 3, March 1920, p. 157; discussion by W. J. Humphreys, p. 157.

B-42. Arnold, James W.: Hailstorm of March 3, 1920, at Broken Arrow, Okla. Monthly Weather Rev., vol. 48, no. 3, March 1920, p. 158. The hailstones were conical in shape, 0.5 inch in diameter, and composed of clear ice.

B-43. Connor, Patrick: Large Hailstones at Kansas City, Mo., May 14, 1898. Monthly Weather Rev., vol. 48, no. 7, July 1920, pp. 398-399. 6 photos. Shows hailstones the size of hen eggs.

B-44. Simes, E. F.: Hailstorm at Wausau, Wis., May 22, 1921. Monthly Weather Rev., vol. 49, no. 6, June 1921, pp. 334-335. Description of stones, some over 5 inches in diameter; damage of $150,000.

B-45. Anon.: What is a Hailstone? Tycos-Rochester, vol. 12, Jan. 1922, pp. 25-26.

B-46. Bevan, Arthur: Peculiar Hail. Science (Washington), New ser., vol. 58, Nov. 30, 1923, pp. 443-444.

B-47. Réthly, Anton: Hailstones Observed at Budapest, July 13, 1922. Monthly Weather Rev., vol. 52, no. 4, April 1924, p. 206. Description and drawings of five hailstones carefully observed by the author.

B-48. Johnson, Harley N.: Severe Hailstorm at Rapid City, S. Dak. and Vicinity, July 18, 1924. Monthly Weather Rev., vol. 52, no. 7, July 1924, p. 349. Illustrated. Size of stones range from peas to small hen eggs.

B-49. Anon.: Hailstones of Size. Tycos-Rochester, vol. 15, July 1925, p. 92.

*B-50. Humphreys, W. J.: Discoidal, Pear-Shaped and Spherical Hailstones. Bull. Am. Meteorol. Soc., vol. 7, no. 8-9, Aug.-Sept. 1926, pp. 103-104. Discussion of structure and method of formation of these shaped hailstones.

B-51. Talman, Charles Fitzhugh: The Biggest Hailstones. Bull. Am. Meteorol. Soc., vol. 9, no. 6-7, June-July 1928, p. 131.

*B-52. Blair, Thomas A.: Hailstones of Great Size at Potter, Nebraska. Monthly Weather Rev., vol. 56, no. 8, Aug. 1928, p. 313. Good description of hailstorm. A picture shows a hailstone 17 inches in circumference weighing 1.5 pounds.

B-53. Brooks, Charles F.: The Biggest Hailstones. Bull. Am. Meteorol. Soc., vol. 9, no. 11, Nov. 1928, p. 184.

B-54. Knipp, Charles T.: Peculiarly Shaped Hailstones. Science (Washington), New ser., vol. 70, Sept. 13, 1929, p. 260. 1 diagram.

1930 - 1939

B-55. Blair, Thomas A.: Sizable Hailstones. Tycos-Rochester, vol. 20, Jan. 1930, p. 29. 1 photo.

*B-56. Anon.: Remarkable Hailstorm in Iraq. Meteorol. Mag. (London), vol. 65, no. 774, July 1930, pp. 143-144. Description of storms on April 24, 1930, at Hinaidi and Bagdad. Large size of hailstones, slow terminal velocity of stones, absence of dust in their composition. Hailstones fell at slow rate of 9 miles per hour and appeared perfectly clear.

B-57. Anon.: Hailstones. Tycos-Rochester, vol. 22, Jan. 1932, p. 12. Occurred at Potter, Neb., July 6, 1928.

B-58. Anon.: What is Graupel? (Soft Hail?) Tycos-Rochester, vol. 22, Jan. 1932, p. 28. 1 photo.

B-59. Blair, Thomas A.: Muddy Hailstones. Bull. Am. Meteorol. Soc., vol. 15, no. 12, Dec. 1934, pp. 307-308. Hailstones fell after a period of 36 days when there had been only 0.08 inch of rain in this part of Nebraska.

B-60. Pierce, Charles H.: Causes for Colored Hailstones. Bull. Am. Meteorol. Soc., vol. 15, no. 12, Dec. 1934, p. 308.

B-61. Pollard. A. E.: Large Hailstones at Northampton. Meteorol. Mag. (London), vol. 71, no. 841, Feb. 1936, pp. 15-16. Storm occurred on Sept. 22, 1935. Description of hailstones.

*B-62. Botley, C.: Shapes of Hailstones. Quarterly Jour. Roy. Meteorol. Soc., vol. 63, no. 271, July 1937, p. 337. Calls attention to illustrations of fantastic shapes of hailstones in Tissandier's "Ocean Aerien".

*B-63. Johnson, R. P.: The Structure of Hailstones. Nature (London), vol. 142, no. 3586, July 23, 1938, p. 172. Reprinted in Monthly Weather Rev., vol. 66, no. 9, Sept. 1938, p. 277. Hailstones which fell in Washington, D. C., April 29, 1938, appeared to be fragments of larger stones, which had been broken below region of formation. It was suggested that a pressure wave resulting from a bolt of lightning caused the shattering.

B-64. Ròdes, L.: Grelons de dimension exceptionelle. (Hail of Exceptional Dimension.) La Météorologie (Paris) 3e Série, Sept.-Oct. 1938, pp. 320-321.

1940 - 1950

*B-65. Brooks, Charles F.: Hail Shells. Bull. Am. Meteorol. Soc., vol. 24, no. 2, Feb. 1943, p. 53. Description of hailstones that fell at Silver Lake, N. H., June 28, 1940, which appeared to be "hastily frozen large wet snow flakes."

*B-66. Arenberg, David L.: The Formation of Small Hail and Snow Pellets. Bull. Am. Meteorol. Soc., vol. 22, no. 3, March 1941, pp. 113-116. 8 figures, 11 references. Describes in detail grains of graupel that fell on Mt. Washington on May 1, 1939, with added note giving possible proof that hailstones can freeze from the surface inward.

*B-67. Trendell, E. R.: Lenticular Hail. Quarterly Jour. Roy. Meteorol. Soc., vol. 70, no. 305, July 1944, p. 195. Very brief description of hailstones of unusual size $\left(1\frac{1}{4}\right.$ in. by $\frac{1}{4}$ to $\left.\frac{3}{8}\text{ in.}\right)$ which fell in London on May 29, 1944.

*B-68. Brooks, C. E. P.: The Frequency Distribution of Hailstone Sizes. Quarterly Jour. Roy. Meteorol. Soc., vol. 70, no. 305, July 1944, pp. 227-228. 1 figure. Tabulation and diagram showing hail sizes that fell in India between 1833-1897.

B-69. Poulter, R. M.: Conical Hail. Quarterly Jour. Roy. Meteorol. Soc., vol. 71, no. 307-308, Jan.-April 1945, p. 125. 1 plate. Gives diameter, shape, and melting time of two distinct types of soft hail.

B-70. Megaw, T. M.: Large Hailstones in the English Midlands. Quarterly Jour. Roy. Meteorol. Soc., vol. 71, no. 307-308, Jan.-April 1945, pp. 150-151. Many hailstones 1.5 inches in diameter. Stones were spherical, nucleus not always centered and side most remote from nucleus was cauliflower-like in texture.

*B-71. Brooks, C. F.: Minimum Water Content of Hail Deposits. Bull. Am. Meteorol. Soc., vol. 26, no. 4, April 1945, p. 122. Very brief note giving water equivalent of layers of hail of different thicknesses.

*B-72. Gerson. N. C.: Variation in Physical Properties and in Atmospheric Concentration of Hail. Bull. Am. Meteorol. Soc., vol. 27, no. 2, Feb. 1946, pp. 47-53; comments by Charles F. Brooks, vol. 27, no. 6, June 1946, p. 358. 12 references. Contains table showing most common range of sizes measured on

the ground; tables giving frequency distribution of hail sizes for India, central Europe, and the United States; temperature within hailstones, temperature of hailstones on the ground, and temperature of hailstones at certain altitudes; horizontal and vertical distributions of hail.

B-73. Lonsdale, Kathleen, and Owston, P. G.: X-Ray Examination of Hail. Nature (London), vol. 157, no. 3989, April 13, 1946, p. 479. Authors unable to complete examination because of accidental interruption of refrigeration where hailstones were kept. Frequently quoted.

B-74. Boyle, P.: An Unusual Fall of Hailstones. Weather (London), vol. 1, no. 5, Sept. 1946, p. 160. Description of three types of hailstones that fell in the area surrounding Shouldham Thorpe, Norfolk, on July 2, 1946. Diameter 2.0 to 2.5 inches; as big as tennis balls when they first fell.

B-75. Anon.: Texas Hailstone Found Larger Than a Baseball. Sci. News Letter, (Washington), vol. 54, no. 8, Aug. 21, 1948, pp. 115-116. Illustrated. Storm occurred on May 3, 1948. Largest hailstone measured 11 inches in circumference.

B-76. Grinstead, W. A.: Unusual Hailstones. Meteorol. Mag. (London), vol. 78, no. 920, Feb. 1949, p. 53. Drawing of star-shaped hailstones.

C.- HAILSTORMS - SINGLE CASES

PREVIOUS TO 1800

C-1. Anon.: Extract of a Letter from Lisle in Flanders, May 25, 1686, Giving an Account of an Unusual Storm of Hail Which Fell There. Phil. Trans. (London), vol. 17, 1693, p. 858.

C-2. Halley, Edmund: Account of an Extraordinary Hail at Chester on the 29th of April 1697. Phil. Trans. (London), vol. 19, 1695-1697, pp. 570-576.

C-3. Taylor, Robert: Account of a Great Hailstorm at Hitchin in Hartfordshire, May 4th 1697. Phil. Trans. (London), vol. 19, 1695-1697, pp. 577-578.

C-4. Lhwyd, Edward: A Note Concerning an Extraordinary Hail on June 6, 1697. Phil. Trans. (London), vol. 19, 1695-1697, pp. 579-580; vol. 27, 1710-1712, p. 469.

C-5. Fauquier, Francis: An Account of an Extraordinary Storm of Hail in Virginia, July 9, 1758. Phil. Trans. (London), vol. 50, pt. 2, 1758, pp. 746-747.

C-6. Tessier, M., and others: Mémoire sur l'orage du dimanche 13 Juillet 1788. (Account of the Storm of Sunday, July 13, 1788.) Academie des Sciences, Histoire (Paris), 1789, pp. 628-638. (Available U. S. Weather Bur. Lib.)

C-7. Dewey, Sherman: Account of a Hail Storm, Which Fell on Part of the Towns of Lebanon, Bozrah and Franklin, on the 15th of July, 1799; Perhaps Never Equaled by Any Other Ever Known, Not Even in Egypt. 12mo. Walpole, Newhampshire, 1799, 27 pp.

1800 - 1849

C-8. Neill, Patrick: Account of a Remarkable Shower of Hail, Which Fell in Orkney on the 24th of July 1818. Edinburgh Phil. Jour., vol. 4, 1821, pp. 365-371. Reprinted in Trans. Roy. Soc. Edinburgh, vol. 9, 1823, pp. 187-200.

C-9. Saul, M.: A Terrific Hailstorm at Lancaster. Mag. Natural History (London), vol. 6, 1833, p. 369.

C-10. Carpenter, W. M.: Notice of a Hailstorm in Louisiana. Am. Jour. Sci. (New Haven), First ser., vol. 27, 1835, p. 171.

C-11. Martin, P. J.: On a Remarkable Fall of Hail, with Observation on the Probable Cause of Such Phenomena. Phil. Mag. (London), vol. 16, 1840, pp. 85-87.

C-12. Jordan, J.: Memoir of the Hailstorm That Occurred in the County of Oxford, on Wednesday, August 9th, 1843. 8vo., (London), 1843.

1850 - 1899

C-13. Birt, W. R.: On the Hailstorm of the 5th of May. Phil. Mag. (London), vol. 36, 1850, pp. 420-422.

C-14. Loomis, Elias: Notice of the Hailstorm Which Passed over New York City on the 1st of July 1853. Am. Jour. Sci. (New Haven), Second ser., vol. 17, 1854, pp. 35-55. Illustrated.

C-15. Barber, J. W.: Connecticut Historical Collections. Hailstorm in Derby, Conn., Feb. 7, 1764. 8vo., (New Haven), 1856, p. 203.

C-16. Barber, J. W.: Connecticut Historical Collections. Hail Storm in Bosrah, Conn., July 1799. 8vo., (New Haven), 1856, p. 302.

C-17. Blakiston, Thomas: Account of a Remarkable Ice Shower. Proc. Roy. Soc. (London), vol. 10, 1859-1860, p. 468. Also in Phil. Mag. (London), vol. 20, 1860, p. 168.

C-18. King, William: Hailstorm in Pontiac. Canadian Naturalist (Montreal), vol. 1, 1864, pp. 307-308. Frog inside a hailstone.

C-19. Blanford, H. F.: Note on the Hailstorm of Thursday, March 24th, 1864. Jour. Asiatic Soc. Bengal (Calcutta), vol. 33, 1865, pp. 530-534. Also in Proc. British Meteorol. Soc. (London), vol. 2, 1863-1865, pp. 456-460.

C-20. Symons, G. J.: On a Periodic Fall of Soft Hail on Snow-Balls, on March 8th. Symons's Meteorol. Mag. (London), vol. 1, 1866, pp. 17-18; vol. 2, 1867, pp. 30-31.

C-21. Slatter, J.: Hailstorm near Oxford, July 5, 1852. Proc. British Meteorol. Soc. (London), vol. 3, 1865-1867, p. 169.

C-22. Anon.: Severe Hailstorm in India. Symons's Meteorol. Mag. (London), vol. 2, 1867, pp. 53-54.

C-23. Jones, S. U.: On a Hailstorm at Leamington, 14th April 1867. Proc. British Meteorol. Soc. (London), vol. 3, 1865-1867, p. 405.

C-24. Emerson, G.: Hailstorm, September 25, 1867. Proc. Am. Phil. Soc. (Philadelphia), vol. 10, 1865-1868, p. 351.

C-25. Hovey, H. C.: The Hail-storm of June 20th, 1870. Am. Jour. Sci. (New Haven), Second ser., vol. 50, 1870, pp. 403-404.

C-26. Bache, G. M.: Account of a Hailstorm in Texas. Smithsonian Report (Washington), 1870, pp. 477-479.

C-27. Porter, David: Account of a Hailstorm on the Bosporus. Smithsonian Report (Washington), 1870, pp. 475-476.

C-28. Joule, J. P.: On the Hailstorm of 4th of January 1872. Proc. Literary and Phil. Soc. (Manchester), vol. 11, 1872, p. 75.

C-29. LaTouche, J. D.: Notes Regarding a Remarkable, and Very Severe Hailstorm Which Occurred in the Neighborhood of Pietermaritzburg, the Capitol of the Colony of Natal, on the 17th of April 1874. Quarterly Jour. Roy. Meteorol. Soc. (London), vol. 2, 1874-1875, pp. 235-236.

C-30. Ley. W. C.: Heavy Local Hail Storms. Symons's Meteorol. Mag. (London), vol. 13, 1878, pp. 72-73, 118-120.

C-31. Ward, M. F.: Hailstorms at Night. Symons's Meteorol. Mag. (London), vol. 13, 1878, p. 183.

C-32. Butler, Nathan: Notes on a Hail Storm Occurring August 18, 1858. Bull. Minnesota Acad. Natural Sci. (Minneapolis), vol. 1, 1873-1879, pp. 315-316.

C-33. Symons, G. J.: The Thunder and Hail Storms of August 2nd-3rd, 1879. Symons's Meteorol. Mag. (London), vol. 14, 1879, pp. 97-113, 125-128.

C-34. Hardeman, G. O.: Severe Hail Storms. Scientific American (New York), Second ser., vol. 43, 1880, p. 122.

C-35. Russell, H. C.: Thunder and Hail Storms in New South Wales. Jour. Roy. Soc. New South Wales (Sydney), vol. 14, 1880, pp. 51-61.

C-36. Allmann, G. J.: Hailstorm in Dorsetshire, Nature (London), vol. 23, 1880-1881, p. 146.

C-37. Anon.: A Remarkable Hailstorm in Arkansas. Scientific American (New York), Second ser., vol. 44, 1881, p. 296.

C-38. Anon.: A South African Hailstorm. Symons's Meteorol. Mag. (London), vol. 17, 1882, p. 55.

C-39. Ward, M. F.: Hailstorm at Ober Grainau, Bavaria, 4th June, 1882. Symons's Meteorol. Mag. (London), vol. 17, 1882, pp. 162-164. Illustrated.

C-40. Capron, J. R.: Hail Storm in Germany, 1882. Symons's Meteorol. Mag. (London), vol. 17, 1882, p. 186.

C-41. Anon.: Extraordinary Hail Storm at Barton, North Lincolnshire. Symons's Meteorol. Mag. (London), vol. 18, 1883, p. 85. (From Hull and North Lincolnshire Times, July 7, 1883.)

C-42. Anon.: A Cape Hailstorm. Symons's Meteorol. Mag. (London), vol. 18, 1883, p. 139.

C-43. Redhouse, J. W.: Remarkable Hailstorm. Quarterly Jour. Roy. Meteorol. Soc., vol. 10, no. 52, Oct. 1884, p. 303. Extract of a passage from the Annals of the Resuli Dynasty of Yemen in Southern Arabia. Amazing hailstone which fell in 1295-1296.

C-44. Phinney, A. J.: Hailstorm of April 17, at Muncie, Ind. Am. Meteorol. Jour. (Detroit), vol. 2, 1885-1886, pp. 59-60. (Available U. S. Weather Bur. Lib.)

C-45. Stathem, I. H.: A Remarkable Hail-Storm. Nature (London), vol. 34, 1886, p. 122.

C-46. Cornish, R.: A Remarkable Hailstorm. Trans. Natural History and Antiquity Soc. (Penzance), vol. 2, 1887, p. 272.

C-47. Whitehorn, E., Jameson, A., Bird, W. B. M., and Stratton, A. C.: Remarkable Hailstorm near Montereau, France. Quarterly Jour. Roy. Meteorol. Soc., vol. 15, Jan. 1889, pp. 47-51. Illustrated.

C-48. Houston, Edwin J.: The Hailstorm at Philadelphia, October 1, 1889. Jour. Franklin Inst. (Philadelphia), Third ser., vol. 98, Nov. 1889, pp. 360-362.

C-49. Russell, Henry C.: Remarkable Hailstorms. Quarterly Jour. Roy. Meteorol. Soc., vol. 19, July 1893, p. 205. Occurred at Tulcumbah, New South Wales on Oct. 13, 1892.

C-50. Vary, Frank W.: The Hailstorm of May 20, 1892. Am. Meteorol. Jour. (Detroit), vol. 10, no. 6, Oct. 1893, pp. 263-273. (Available U. S. Weather Bur. Lib.) 5 figures. Describes

storm of uncommon violence affecting southeastern Ohio, southwestern Pennsylvania and the northern part of West Virginia. Drawings of cross sections and description of two hailstones picked up by author. Map showing advancing edge of cloud belt. Two photographs showing evidence of destruction.

C-51. Marriott, William: Thunder and Hail Storms over England and the South of Scotland, July 8, 1893. Quarterly Jour. Roy. Meteorol. Soc., vol. 20, Jan. 1894, pp. 31-43. Several maps, graphs, and diagrams.

C-52. Coates, J. M.: Hailstorm in Lincolnshire, (England), August 22, 1893. Quarterly Jour. Roy. Meteorol. Soc., vol. 20, Jan. 1894, pp. 72-73. 1 diagram.

C-53. Abbe, Cleveland, ed.: Remarkable Hail. Monthly Weather Rev., vol. 22, no. 5, May 1894, p. 215. Storm occurred at Vicksburg, Miss. on May 11, 1894.

C-54. Hardin, Charles: Hailstorm in the South-West of London, April 27, 1897. Quarterly Jour. Roy. Meteorol. Soc., vol. 23, Oct. 1897, pp. 298-304. Several maps and tables.

C-55. Hackett, A. E.: Severe Hailstorm in Missouri. Monthly Weather Rev., vol. 26, no. 9, Sept. 1898, pp. 409-410. Illustrated. Account sent by J. R. Brink, voluntary observer. Storm occurred September 5, 1898 in northern Missouri. Path of storm 3 miles wide. Cylindrical shape hailstones 4 inches long and 2.5 inches in diameter. Average depth of hail 4 to 6 inches. Drifts of hail remained on ground for 4 weeks after storm.

C-56. Anon.: One of the Most Violent Hailstorms. Scientific American (New York), Second ser., vol. 81, July 22, 1899, p. 58. Storm occurred at Madrid, Spain.

1900 - 1919

C-57. Abbe, Cleveland, ed.: Hailstorm on the St. Lawrence. Monthly Weather Rev., vol. 29, no. 11, Nov. 1901, pp. 506-507. Originally reported by H. S. Chandler.

C-58. Abbe, Cleveland, ed.: Severe Hailstorm at St. Louis. Mo. Monthly Weather Rev., vol. 30, no. 10, Oct. 1902, p. 487. Storm occurred Oct. 12, 1902. Remarkable for occurrence at night and size of stones. Lasted only 7 minutes but most severe storm ever experienced in St. Louis.

C-59. Wilson, Alfred W. G.: A Peculiar Hailstorm. Science (Washington), New ser., vol. 16, Dec. 10, 1902, pp. 909-910.

*C-60. Alexander, W. H.: Hailstorms in Porto Rico. Monthly Weather Rev., vol. XXXI, no. 5, May 1903, pp. 233-234. Track of hailstorm of April 12, 1903, shown on map.

C-61. Cellini, Benvenuto: Autobiography of Benvenuto Cellini. An Italian Hailstorm in 1545. London, 1903, vol. 2, p. 88. Reprinted in Monthly Weather Rev., vol. 32, no. 7, July 1904, p. 324. Storm occurred south of Lyon during July 1545.

C-62. Slaughter, J. Pamberton: Hailstorm at Pueblo, Colo. Monthly Weather Rev., vol. 32, no. 7, July 1904, p. 319.

C-63. Abbe, Cleveland, ed.: Hailstorm in the Bahamas. Monthly Weather Rev., vol. 33, no. 6, July 1905. p. 260. Storm occurred on the Island of Spanish Wells, April 18, 1905.

C-64. Abbe, Cleveland, ed.: A Severe Hailstorm at Grand Rapids, Mich. Monthly Weather Rev., vol. 33, no. 7, July 1905, p. 324. Originally reported by C. F. Schneider. Storm occurred on May 4, 1905.

C-65. Bindley, R. G.: Hailstorm in the Gulf of Mexico, March 18, 1906. Monthly Weather Rev., vol. 34, no. 5, May 1906, p. 226. Reprinted in Quarterly Jour. Roy. Meteorol. Soc., vol. 32, July 1906, pp. 236-237.

C-66. Anon.: Destructive Hailstorm in Bedfordshire, August 2, 1906. Quarterly Jour. Roy. Meteorol. Soc., vol. 33, Jan. 1907, pp. 60-63.

C-67. Anon.: Hailstorm at Lewisham, June 25, 1652. Quarterly Jour. Roy. Meteorol. Soc., vol. 33, Jan. 1907, pp. 65-66.

C-68. Allerton, Thomas E.: Hailstorm at Charlestown, Natal, October 24, 1906. Quarterly Jour. Roy. Meteorol. Soc., vol. 33, April 1907, pp. 181-182. Illustrated.

C-69. Violle, J.: (A Hailstorm Followed the Course of an Electric Transmission Line.) Comptes Rendus (Paris), tome 147, Aug. 17, 1908, pp. 375-377. Describes the course of a hail storm along a high voltage transmission line that had only been in use for a year. The storm extended over an area 14 kilometers by 2 kilometers. The direction of the movement of this storm was not unusual for this area.

C-70. Von Herrmann, Charles F.: The Severe Hailstorm at Atlanta. Monthly Weather Rev., vol. 37, no. 10, Oct. 1909, pp 710-711. Storm occurred on October 14, 1909. Stones varied from 0.5 to 2.5 or 3.0 inches in diameter. Street railway and telephone systems disorganized for a time.

C-71. Russell, Spencer C.: Hail and Thunderstorm on May 8, 1910, at Epsom. Quarterly Jour. Roy. Meteorol. Soc., vol. 36, July 1910, pp. 295-296. 1 table, 1 diagram.

C-72. Sullivan, Richard H.: Severe Local Storm, September 6, 1911. Monthly Weather Rev., vol. 39, no. 9, Sept. 1911, pp. 1382-1383. Storm occurred at Wichita, Kansas.

C-73. Jones, A. H., and Wheeler, D. W.: Phenomenal Hailstones at Gavarnie, August 6, 1911. Quarterly Jour. Roy. Meteorol. Soc., vol. 37, no. 160, Oct. 1911, pp. 361-363. Gavarnie is in the Pyrenees. Plaster cast of hailstone in comparison with penny is shown in photo.

C-74. Anon.: Hail in the Tropics. Monthly Weather Rev., vol. 40, no. 6, June 1912, p. 969. Extract from the Canal (Zone) Records of July 3, 1912.

C-75. Byram, John W.: A Severe Storm at Concordia, Kansas. Monthly Weather Rev., vol. 40, no. 8, Aug. 1912, p. 1203. Storm occurred on August 5-6, 1912.

C-76. Anon.: (Hailstorm That Devastated the Plain of Owari.) Aichiken Meteorological Observatory, Nagoya, Japan, 1912. (Available U. S. Weather Bur. Lib.) Several photos, maps, and charts. Pages in Japanese and unnumbered. Hail fell on April 19, 1912. Photos show damage, shape, and structure of stones.

C-77. Scott, James H.: Severe Hailstorm on James Island, S. C. Monthly Weather Rev., vol. 41, no. 5, May 1913, p. 676. Storm occurred May 10, 1913. Cotton and truck crops severely damaged.

C-78. Mitchell, Alexander J.: Severe Wind and Hailstorms in Florida. Monthly Weather Rev., vol. 41, no. 6, June 1913, p. 828. Storm occurred on June 18, 1913.

C-79. Day, Preston C.: Thunderstorm of July 30, 1913, at Washington, D. C. Monthly Weather Rev., vol. 41, no. 7, July 1913, p. 969.

C-80. Kimball, James H.: Local Storms of July 19, 1913, in Virginia. Monthly Weather Rev., vol. 41, no. 7, July 1913, pp. 981-982.

C-81. Fassig, Oliver L.: A Remarkable Fall of Hail in Maryland. Monthly Weather Rev., vol. 43, no. 9, Sept. 1915, pp. 446-448. 1 photo, several maps. Occurred on June 22, 1915.

C-82. Anon.: Unusual Hailstorm at Ballinger, Texas. Monthly Weather Rev., vol. 45, no. 3, March 1917, p. 118. Reported by E. M. Eubank. Hail Fell on March 16, 1917; did not disappear completely until 7 days later.

C-83. Hirshberg, Leonard Keene: Hail Squall of May 1, 1917, and Accompanying Weather, Baltimore, Md. Monthly Weather Rev., vol. 45, no. 5, May 1917, pp. 236-237.

C-84. Loveland, George A.: Nebraska Hailstorm of August 8, 1917. Monthly Weather Rev., vol. 45, no. 11, Nov. 1917, pp. 540-542. A map shows path of storm through Eastern Nebraska. Enormous quantities of hail fell; considerable property loss.

*C-85. Howchin, Walter: Notes on the Remarkable Hailstorm near Adelaide, on May 12, 1917. Trans. and Proc. Roy. Soc. South Australia (Adelaide), vol. XLI, Dec. 24, 1917, pp. 323-332 and plate XVI. Describes the hailstorm and discusses briefly hail formation.

C-86. Carpenter, Ford Ashman: Whirlwind of January 26, 1918, at Pasadena, Calif. Monthly Weather Rev., vol. 46, no. 4, April 1918, pp. 178-179. 1 photo, 1 graph. Includes an excellent full-page picture of this whirlwind. Hail fell several inches deep over a very small area.

C-87. Hauptmann, Noritz (A. D. Coleridge, trans.): Hailstorm in 1860, Leipzig. Quarterly Jour. Roy. Meteorol. Soc., vol. 44, no. 186, April 1918, p. 97. Letter originally written on Sept. 5, 1860.

*C-88. Beebe, William: A Kashmir Barrage of Hail. Scientific American Supplement No. 2221 (New York), vol. LXXXVI, July 27, 1918, p. 55. Reprint from Bull. N. Y. Zoological Soc. (Available U. S. Weather Bur. Lib.) Description of violent hailstorm in the western Himalayas.

C-89. Sullivan, Richard H.: Hailstorms in South Carolina, June 8 and 9, 1919. Monthly Weather Rev., vol. 47, no. 6, June 1919, p. 393. Location and extent of storms shown on map.

1920 - 1929

C-90. Smythe, P. H.: The Hailstorm of April 8, 1920 in Washington County, Alabama. Monthly Weather Rev., vol. 48, no. 4, April 1920, p. 213.

C-91. Clark, J. Edmund: The Surrey Hailstorm of July 16, 1918. Quarterly Jour. Roy. Meteorol. Soc,, vol. 46, July 1920, pp. 271-288. Several tables, maps, and diagrams.

C-92. Alter, J. Cecil: Hailstorm at Lehi, Utah. Monthly Weather Rev., vol. 48, no. 8, Aug. 1920, pp. 451-452. Illustrated. Presents the most destructive hailstorm on record in the state, size and shape of stones, and crop damage.

C-93. Carter, Harry G.: Severe Hailstorm in Nebraska. Monthly Weather Rev., vol. 49, no. 1, Jan. 1921, pp. 22-24. Figures show area of severe storm of July 16, 1920.

C-94. Horton, Edgar C.: Hailstorm near Birmingham, Ala., May 11, 1921. Monthly Weather Rev., vol. 49, no. 6, June 1921, p. 334. Details given of unusually large hailstones and damage.

C-95. Smythe, Patrick H.: Hailstorm in Alabama, November 14, 1921. Monthly Weather Rev., vol. 49, no. 12, Dec. 1921, pp. 659-660. Occurrence of hailstones over a portion of Alabama is shown on a map.

C-96. Anon.: Severe Hailstorm near West Chester, Pa. Monthly Weather Rev., vol. 50, no. 8, Aug. 1922, p. 425. Originally reported by J. T. Brosius. Storm occurred on July 31, 1922.

C-97. Anon.: Severe Hailstorm at Corpus Christi, Tex. Monthly Weather Rev., vol. 52, no. 4, April 1924, p. 205. Originally reported by J. P. McAuliffe.

C-98. Anon.: A Notable Hailstorm on July 5, 1891. Monthly Weather Rev., vol. 52, no. 7, July 1924, p. 349. From notes at the Rapid City Weather Station of July 5, 1891, by Wm. Norrington, Observer, Signal Corps.

C-99. Varney, Burton M.: The Great Hailstorm in Southeastern New Hampshire and Northeastern Massacusetts, July 17, 1924. Monthly Weather Rev., vol. 52, no. 8, Aug. 1924, pp. 394-395.

C-100. Anon.: The Flooding of a Pasture by Hail. Monthly Weather Rev., vol. 53, no. 6, June 1925, p. 261. Originally reported by Edwin T. Larsen.

C-101. Spencer, James H.: Hailstorm on Sunday Afternoon, May 24, 1925, at Baltimore, Maryland. Monthly Weather Rev., vol. 53, no. 6, June 1925, pp. 261-262. Followed hottest weather ever recorded for May in Baltimore. Size and shape of stones. Damage chiefly to greenhouse glass.

C-102. Anon.: Unusual Hail in East. Bull. Am. Meteorol. Soc., vol. 6, no. 7, July 1925, p. 112. Occurred in New York, May 23, 1925.

*C-103. Cline, Joseph L.: Hailstorm at Dallas, Texas, May 8, 1926. Monthly Weather Rev., vol. 54, no. 5, May 1926, p. 216. Hail fell for 21 minutes. Size varied from 0.5 to 4 inches in diameter. Larger stones had five to eight layers and weighed 22 ounces. Damage estimated at $750,000.

C-104. Bartniccy, St. i L., and Klimowicz, W.: Burze i orkan w Polsce w dniu 26 Kivietnia 1926. (Unexpected Storms and Gales in Poland on April 26, 1926.) Państwowy Instytut Meteorologiczny (Warsaw), 1926, 13 pp. (Available U. S. Weather Bur. Lib.) 1 table, several maps. Summary in French pp. 12-13. Brief mention of hail that accompanied storm. Several zones of hail are traced and shown on map.

*C-105. Brunt, D.: Remarkable Hailstorm. Meteorol. Mag. (London), vol. 63, Feb. 1928, pp. 14-15. Description only. Surface distribution peculiar.

C-106. Parker, H. P.: A Medieval Hailstorm (1545). Bull. Am. Meteorol. Soc., vol. 9, no. 6-7, June-July 1928, pp. 130-131.

C-107. Talman, Charles Fitzhugh: An Amazing Hailstorm. Bull. Am. Meteorol. Soc., vol. 9, no. 6-7, June-July 1928, p. 131. Storm occurred in Kansas, June 4, 1927.

*C-108. Ellison, William F. A.: Remarkable Thunderstorm at Armagh. Meteorol. Mag. (London), vol. 63, Oct. 1928, pp. 208-209. Description only. Armagh is in Northern Ireland.

*C-109. Kendall, J. L., Barron, W. E., and Dyke, R. A.: Hail, April 21, 1929, in Kentucky, Illinois and Louisiana. Monthly Weather Rev., vol. 57, no. 4, April 1929, pp. 157-158. Brief account of hail occurrence for Louisville, Kentucky; lower Ohio Valley; and northeast Louisiana. Each section written by one of the authors.

*C-110. Richardson, Herbert W.: Hailstorm at Duluth, Minn., June 10, 1929. Monthly Weather Rev., vol. 57, no. 6, June 1929, pp. 255-256. Hailstone size: marbles to baseballs. Damage: store windows, street lights, auto windows, and so forth.

C-111. Carey, Fred: Hailstorm of 1881 Stands As a Record. Bull. Am. Meteorol. Soc., vol. 10, no. 11, Nov. 1929, pp. 204-205. Hailstorm combined with tornado and cloudburst; stones the size of small heads of cabbage. Extensive damage to houses and farm buildings. Horses, cattle, hogs, and chickens killed. Growing crops ruined and trees stripped of fruit and foliage.

1930 - 1939

*C-112. Greening, Gershom K.: Hailstorm of September 7, 1930, across Extreme Southeastern South Dakota and Northwestern Iowa. Monthly Weather Rev., vol. 58, no. 9, Sept. 1930, p. 365. 3 figures. Storm track 5 by 60 miles. Damage estimated at $1,000,000, mostly to corn.

C-113. Mears, F. C.: Thunderstorm, August 28, 1930. Meteorol. Mag. (London), vol. 66, Feb. 1931, pp. 15-17.

*C-114. Russell, Richard Joel: Hailstorm of April 20, 1933, Baton Rouge, La., Bull. Am. Meteorol. Soc., vol. 14, no. 6-7, June-July 1933, pp. 177-178.

C-115. Barron, William E.: Terrific Hail In Saskatchewan. Bull. Am. Meteorol. Soc., vol. 14, no. 10, Oct. 1933, pp. 243-244. From Regina Leader Post.

C-116. Anon.: Line Squalls and Heavy Rain in Iraq and Palestine on May 14-15, 1934. Meteorol. Mag. (London), vol. 69, Sept. 1934, pp. 185-191.

C-117. Primavesi, R. H.: Thunderstorms and Hailstones, Sunday, September 22, 1935. Jour. Natural History Soc., (Northampton), vol. 28, 1935, pp. 19-21.

C-118. Rodewald, Martin: Das Hagelunwetter in der Zone Hildesheim-Peine vom 18, Juli 1936. Wetterskizzen Nr. 11. (Hailstorm in the Hildersheim-Peine Zone on July 18, 1936. Weathersketch No. 11.) Annalen der Hydrographie und Maritimen Meteorologie (Hamburg), Bd. 64, Heft 10, Oct. 1936, pp. 447-448. (Available at the Lib. of Congress.) Synoptic conditions in connection with one of the worst hailstorms in the Hannover-Brunswick portion of Germany.

C-119. Hookham, A. H.: Hailstorm at Eastbourne, July 7th, 1938, Meteorol. Mag. (London), vol. 73, no. 871, Aug. 1938, p. 179.

C-120. Neville, Norman E.: Hailstorm near Winchester, July 7, 1938, Meteorol. Mag. (London), vol. 73, no. 871, Aug. 1938, p. 179.

*C-121. Slocum, Giles: Unusual Fall of Large Hailstones at Washington, D. C. Monthly Weather Rev., vol. 66, no. 9, Sept. 1938, p. 275. Describes the hailstorm of April 29, 1938. Two pictures of hailstones.

C-122. Pinkhof, M.: Merkwaardige Windhoozen en hagelval bij Hondeloopen op 12 Aug. 1938. (Remarkable Tornadoes and Hailfall near Hondeloopen on Aug. 12, 1938.) Hemel en Dampkring (The Hague), deel 36, 1938, pp. 348-361. (Available U. S. Weather Bur. Lib.)

*C-123. Canaday, G. L.: Hail and Windstorm over South-Eastern Louisiana, February 26, 1939. Monthly Weather Rev., vol. 67, no. 10, Oct. 1939, pp. 365-366, 4 figures. Path of storm, size and depth of hailstones, wind velocity and damage.

C-124. Anon.: Hailstorm in New Orleans - a Rare Phenomenon. Taylor-Rochester, vol. 29, no. 2, 1939, pp. 58-59. Details of the most destructive hailstorm in several decades which was accompanied by lightning, thunder, and high wind. Storm was result of a violent thunderstorm-type condition which covered a large area.

1940 - 1950

C-125. Little, E. W. R.: Observations on Hail. Quarterly Jour, Roy. Meteorol. Soc., vol. 66, no. 283, Jan. 1940, pp. 21-22. Brief account of two hailstorms on Oct. 27, 1939, in Durham, England, where hail is a winter phenomenon. In both cases air temperature was slightly above freezing which may have been responsible for the formation of stones resembling bundles of fibers.

C-126. Rossman, F.: Ein bemerkenswerter Hagelfall: Sehr grosse, vereinzelt fallende Hagelstein. (A Remarkable Hailfall: Very Large, Scattered Hailstones.) Meteorol. Zeitschr. (Brunswick), Bd. 57, Heft 1, Jan. 1940, pp. 43-45. 2 figures. An analytical account of a thunderstorm situation in Bavaria on May 27, 1931. The stones were formed of concentric layers and were dry. An adiabatic chart for that day made from a sounding at Friedrichshafen shows the tremendous amount of energy available for convective activity.

*C-127. Williford, C. C.: Black Dust with Hail, Snow and Rain. Bull. Am. Meteorol. Soc., vol. 22, no. 3, March 1941, pp. 122-124. Description of a Missouri hailstorm with black hail. Correspondence with the U. S. Bureau of Mines concerning the chemical content of the dust is quoted.

C-128. Botley, Cicely M.: A Hail Storm in Cape Colony. Quarterly Jour. Roy. Meteorol. Soc., vol. 68, no. 297, Oct. 1942, p. 301. A very brief note of hailstorms in Umtata. Average size of stones was larger than hen eggs.

C-129. Anon.: L'orage a grêle du 29 Juin 1944 dans le nord du Loir-et-Cher. (Hailstorm on June 29, 1944 in Northern Loir-et-Cher.) La Météorologie (Paris), 3e serie, Jan.-June 1944, pp. 111-112. Brief account of area and damage of hailstorm with stones as as large as oranges.

*C-130. Conover, John H.: "Baseball" Hail from Towering Cumulonimbus. Weather (London), vol. 1, no. 7, Nov. 1946, p. 217. 2 photos. Pictures were taken at Blue Hill Observatory on July 4, 1944, while cumulonimbus was dropping baseball-sized hailstones on Taunton, Mass., which was about 20 miles away.

C-131. Lucas, Gabriel: Observations de grêlons. (Hail Observations.) La Nature (Paris), tome 74, no. 3126, Dec. 15, 1946, p. 383. 2 figures. Unusual fall of hail in Brittany (where hail is not frequent) on May 27, 1931. Hailstones 35 millimeters in diameter. Crops destroyed.

C-132. Anon.: Grêlons monstruex. (Tremendous Hailstones.) La Nature (Paris), tome 75, no. 3129, Feb. 1, 1947, p. 43. Brief account of hailstorm in Sydney, Australia, on Jan. 1, 1947, in which 210 persons were hospitalized and extensive property damage incurred.

C-133. Knoche, Walter: Observaciones de un enfriamiento súbito debido a una graizada fina. (Observations of a Sudden Fall of Temperature Following a Hailstorm.) Revista Meteorológica (Montevideo), Año 6, no. 22, April 1947, pp. 128-130. (Available U. S. Weather Bur. Lib.) Tables. Data based on a storm at Cordoba. Table gives for every hour of the day: dry and wet temperature; wind direction and velocity; cloud formation. Comments on meteoropathological significance of sudden cooling of temperature.

C-134. Milthorpe, W.: An Account of the Severe Hailstorm at Charlesville, Queensland, on 23rd November, 1947. Weather Development and Research Bulletin No. 10, R.A.A.F. (Melbourne), June 1948, pp. 21-22. (Available U. S. Weather Bur. Lib.) 2 photos, 1 chart. Covers synoptic situation, upper air conditions, formation of storm, area of storm, and damage.

C-135. Dwyer, W. N., and McIntyre, D. G.: Hailstorm at Western Junction on 31st October, 1948. Weather Development and Research Bulletin, No. 12, R.A.A.F. (Melbourne), March 1949, pp. 43-44; comments p. 69. (Available U. S. Weather Bur. Lib.) Several figures and photos. Synoptic situation preceding storm described. Subsequent weather changes noted: change in wind, lightning and thunder, heavy fall of hail, rain, and drop in temperature. Emphasized effect of topography.

C-136. Klug, P.: Der Hagelsturm vom 2 August 1948 und seine Katastrophale Auswirkung auf die Landwirtschaft im "Klutzer Winkle". (The Hailstorm of August 2, 1948, and Its Catastrophic Effect on Agriculture in the "Klutzer Corner".) Zietschr. für Meteorologie (Potsdam), Bd. 3, Heft, April 1949, pp. 115-116. North Germany, especially northwest Mecklenburg, suffered a severe thunderstorm with hail squalls (force 11) which did enormous damage over an area of 75 square kilometers.

C-137. Hariharan, P. S.: Sizes of Hailstones. Indian Jour. of Meteorology and Geophysics (Delhi), vol. 1, no. 1, Jan. 1950, p. 73. (Available U. S. Weather Bur. Lib.) Account of hailstorms in the Hyderabad State of India on March 17 and 18, 1939. The largest hailstones that fell on the first day weighed 7.5 pounds each, the largest on the second day weighed 5 pounds. The storm of March 17 affected 17 villages in an area of 30 square miles.

D.- HAIL FREQUENCY AND DISTRIBUTION

1810 - 1849

D-1. Anon.: Some of the Phenomena of Summer Hail Storms in America. Med. Rep. (New York), vol. 13, 1810, pp. 186-187.

D-2. Hamilton, William: Some Particulars Respecting Hail Storms in the West Indies in the Month of April 1814; and Experiments to Ascertain the Medicinal Power of the Hura Crepitans. Phil. Mag. (London), vol. 44, 1814, pp. 191-193.

D-3. Christie, A. T.: On Indian Hailstorms. Edinburgh New Phil. Jour., vol. 10. 1831, pp. 308-310.

D-4. Olmsted, Denison: Reply to Dr. Christie on Hailstorms. Am. Jour. Sci., (New Haven), First ser., vol. 20, 1831, pp. 373-376.

D-5. Jones, Alexander: On Hail Storms. Am. Jour. Sci. (New Haven), First ser., vol. 23, 1833, pp. 35-37. Illustrated.

D-6. Taylor, R. C.: Notes on the Weather of Philipsburg, Pennsylvania, from November 1831 to December 1832; with Remarks on Its Influence on Certain Animals and Plants, Including a Detailed Description of a North American "Ice Storm." Mag. Natural History (London), vol. 6, 1833, pp. 97-103.

1850 -1899

D-7. Buist, George: A Catalogue of the Most Remarkable Hailstorms Which Have Occurred in India between 1822 and 1850. Trans. Geographical Soc. (Bombay), vol. 9, 1850, pp. 184-194.

D-8. Tikouravoff, C. N.: (On Hailstones in the Government of Vladimir 1845-1950.) Vjestnik Russk. Geograficheskoe Obshtchestvo, St. Petersburg (Leningrad), Tom. 3, 1851, pp. 66-76.

D-9. Sykes, W. H.: On Indian Hailstorms. Am. Jour. Sci. (New Haven), Second ser., vol. 13, 1852, pp. 294-296. From Rep. British Assoc. (London), 1850, pt. 2, pp. 43-44.

D-10. Poey, Andre: On the Probable Increase in the Number of Hailstorms Occurring in Cuba. Proc. Am. Assoc. (for Advancement of Sci.) (Washington), 1854, pp. 179-187.

D-11. Smyth, R. B.: On the Phenomena of Hailstorms in Victoria. Trans. Phil. Inst. Victoria (Melbourne), vol. 1, 1856, pp. 135-138.

D-12. Abich, W. H.: (On Hail in Kartalinia.) Izvestia Russk. Geograficheskoe Obshtchestvo, St. Petersburg (Leningrad), Tom. 6, 1870, pp. 133-143.

D-13. Buist, George: Remarkable Hailstorms in India from March 1851 to May 1855. Trans. Georgraphical Soc. (Bombay), vol. 12, 1876, pp. 1-25. From Rep. British Assoc. (London), pt. 2, 1855, pp. 31-38.

D-14. Anon.: Increase of Thunder and Hailstorms in Europe. Am. Meteorol. Jour. (Detroit), vol. 3, 1886-1887, pp. 106-108. (Available U. S. Weather Bur. Lib.)

D-15. Hill, S. A.: The Tornadoes and Hailstorms of April and May, 1888; in the Doab and Rohilkhand. Baptist Mission Press (Calcutta), 1889, pp. 135-180. Reprinted from Jour. Asiatic Soc. Bengal, vol. 58, pt. 2, no. 2, 1889. (Available U. S. Weather Bur. Lib.) Several plates and tables. General weather of the period. Number, times of occurrence, duration, and paths of the tornadoes of the 30th of April and 1st of May. Direction and force of the wind in these storms. Electrical phenomena. Hail. Destruction of life and property. Relations of tornadoes to other meteorological phenomena.

D-16. Harries, Henry: The Frequency, Size and Distribution of Hail at Sea. Quarterly Jour. Roy. Meteorol. Soc., vol. 21, Oct. 1895, pp. 230-244. 1 table.

D-17. Abbe, Cleveland, ed.: Depth of Hail Fall. Monthly Weather Rev., vol. 25, no. 9, Sept. 1897, p. 399. Information on several storms including hailstorm of June 24, 1897, at Topeka, Kansas, where size of hailstones averaged 4 inches in diameter with a maximum of 6 inches.

D-18. De Riemer, Alicia, and Abbe, Cleveland: The Average Frequency of Days of Hail during 1893-1897. Monthly Weather Rev., vol. 26, no. 12, Dec. 1898, pp. 546-547. 2 tables.

D-19. Eliot, Sir John: Hailstorms in India during the Period 1883-1897 with a Discussion on Their Distribution. Indian Meteorol. Memoirs (Delhi), vol. 6, pt. 4, 1899, pp. 237-315. (Available U. S. Weather Bur. Lib.) 4 maps, numerous tables. Tables give date, area affected, hour of occurrence, duration, direction from which storm came, size or weight of largest stones, character of storm, and damage for various provinces of India.

1900 - 1919

D-20. Abbe, Cleveland, ed.: The Frequency of Hail in the United States. Monthly Weather Rev., vol. 28, no. 9, Sept. 1900, pp. 396-397. 2 tables.

D-21. Abbe, Cleveland, ed.: Hail and Thunderstorms in Oregon. Monthly Weather Rev., vol. 29, no. 6, June 1901, pp. 262-263. Contains reports by J. S. Churchill, J. C. Brattain, and G. Muecke.

D-22. Monti, V.: Mountains and Hail. Scientific American (New York), Second ser., vol. 86, June 28, 1902, p. 451.

D-23. Vallot, J.: (Hail and Hoar-Frost on Mont Blanc.) Computes Rendus (Paris), tome 154, June 10, 1912, pp. 1650-1652. At this location hail is usually accompanied by a deposition of hoar-frost which is deposited on corners or sharp edges and grows in the windward direction.

D-24. Angot, C. Alfred (W. G. Reed, trans.): Thunder and Hail in the Paris Region. Monthly Weather Rev., vol. 44, no. 12, Dec. 1916, p. 679. Includes table showing thunderstorms and hailstorms by month for a 40 year period.

*D-25. Henry, Alfred J.: Hail in the United States. Monthly Weather Rev., vol. 45, no. 3, March 1917, pp. 94-99. Several tables. Geographic distribution; seasonal distribution; damage to crops by hail; distribution of hail in general (Württemberg and India); theories of hail formation. Tables give average number of days with hail, 1906-1915, for various regions of the United States.

1920 - 1929

D-26. Carter, Harry G.: Hailstorms in Nebraska. Monthly Weather Rev., vol. 48, no. 7, July 1920, pp. 397-398. 4 tables. Tables give the frequency of hail, frequency of thunderstorms, and percentage of thunderstorms with hail in Nebraska.

*D-27. Grigorov, G.: Data Regarding the Distribution and Intensity of Hail in Bulgaria. International Review of the Science and Practice of Agriculture (Rome), Year XIII, no. 8, Aug. 1922, pp. 939-940. (Available U. S. Dept. Agric. Lib.) Abstracted from Semledelie, Sofia, Year XXV, pt. 8, Aug. 1921, pp. 121-122. Contains a table showing the yearly distribution of hail in Bulgaria.

D-28. Visher, Stephen S.: Hail in the Tropics. Bull. Am. Meteorol, Soc., vol. 3, no. 7-8, July-Aug. 1922, pp. 117-118. Cites records of hailstorms in the tropics; Queensland, Australia; Fiju Islands; and Hawaiian Islands.

D-29. Whittier, Bernard B.: Some Data on Hail in Michigan. Bull. Am. Meteorol. Soc., vol. 4, no. 8-9, Aug.-Sept. 1923, pp. 127-128.

D-30. Dyke, Ray A.: Heavy Hailstorm and Local Squall at New Orleans, La., with a Summary of the Previous Records of Hail. Monthly Weather Rev., vol. 52, no. 4, April 1924, p. 205.

D-31. Seeley, Dewey A., and Dole, Robert B.: Hailstorms in Michigan. Monthly Weather Rev., vol. 52, no. 4, April 1924, pp. 195-205. 8 figures. Day by day record of storms in Michigan for 1920-1923 inclusive. Estimate of damage frequently given. Maps show hailstorm occurrence by month.

D-32. Hoxmark, Guillermo: Granizo en la República Argentina. (Hail in the Argentine Republic.) Talares Gráficos del Ministerio de Agricultura de la Nación (Buenos Aires), 1927, 35pp. (Available U. S. Weather Bur. Lib.) 29 figures, 4 tables. Article deals with hail formation, hail classification, protection against hailstorms, hail frequency, and destructive hailstorms in 1926. Charts show average annual and monthly hailstorm frequency.

D-33. Pirou, Antony: Les orges à grêle en France. (Hailstorms in France.) La Météorolgie (Paris), New série, no. 52-54, July-Sept. 1929, pp. 428-441. (Available U. S. Weather Bur. Lib.) Tables.

D-34. Talman, Charles Fitzhugh: Hail in the United States. Bull. Am. Meteorol. Soc., vol. 10, no. 11, Nov. 1929, p. 204.

*D-35. Flora, S. D.: Hailstorms of 1929 in the United States. Bull. Am. Weather Rev., vol. 57, no. 12, Dec. 1929, pp. 509-510. 1 table. Greatest damage for year at Hartford, Conn. on August 1st.

*D-36. Selga, Rev. Miguel: Hail in the Philippines. Manila Central Observatory, Weather Bur., The Government of the Philippine Islands, 1929. (Available U. S. Weather Bur. Lib.) Gives 60 specific cases of hail from 1656 through 1928. First part gives the facts and second part attempts to explain the facts. Thunderstorms are 100 times more frequent than hailstorms. There are included 25 references, mostly from Philippine documents.

1930 - 1939

D-37. Moran, C.: Hailstorms Frequent in Middle Plains Area. Tycos-Rochester, vol. 20, Jan. 1930, p. 29.

D-38. Talman, Charles Fitzhugh: Big Hailstorms. Bull. Am. Meteorol. Soc., vol. 13, no. 8-9, Aug.-Sept. 1932, pp. 158-159.

D-39. Kozaroff, P.: Des chutes de grêle désastreuses en Bulgarie durant les dix dernièrs années. (Disastrous Hailstorms in Bulgaria during the past Ten Years.) Matériaux pour l'Étude des Calamités (Geneva), tome 32, no. 4, 1933, pp. 349-352. (Available U. S. Weather Bur. Lib.) 1 table. Hail usually occurs from middle of April to end of September with the most disastrous storms coming in June and July. Four worst storms in 10 year period took place in 1923, 1926, 1929, and 1932. These storms are described.

D-40. Gumiński, R.: Grady w wojewodztwie Tarnopolskiem (w okresie od r. 1926 do r. 1933). (Track of Hailstorms in the Tarnopol Region (in the Period from 1926 to 1933)). Prace, Fasc. 4 (Reps. No. 4), Państwowy Instytut Meteorologiczny (Warsaw), 1934, pp. 3-13. (Available U. S. Weather Bur. Lib.) 2 figures, 3 tables. Summary in German pp. 12-13. Advances opinion that hail occurrences are in correlation with the structure of the earth's crust. Gives hail distribution in the Ukraine.

D-41. Paoloni, P. D. Bernardo M.: Circa una Prossima Pubblicazione Sulla Distribuzione e sui danni della Grandine in Italia. (About a Recent Publication on Hail Distribution and Damage in Italy.) La Meteorologia Practica, tomo 16, no. 5-6, Sept,-Dec., 1935, pp. 244-252. (Available U. S. Weather Bur. Lib.) Table of frequency of hail disasters in 4,000 communities for years 1925-1935 arranged by provinces. Number of disasters in a large number of communities, monthly frequency of disasters, data of most disastrous storm and insurance odds are given.

D-42. Kunze, G.: Die Räumliche Verteilung der Hagelwetter in Schlesion. (The Areal Distribution of Hailstorms in Silesia.) Meteorol. Zeitschr. (Brunswick), Bd. 53, Heft 3, March 1936, pp. 102-105. 6 figures. Hail damage frequency is given for each of the years from 1930 to 1934. The author claims that analysis of the data shows no relation between orography, temperature, wind direction, or air masses and hail frequency, and a slight correlation between air pressure, wind speed or short-wave reception, and hail damage. Results agree with those found in a similar study for East Prussia. Methods of analysis not too sound.

D-43. Ward, Robert DeCourcy, and Brooks, Charles F.: The Climates of North America I. Bd. II of Handbuch der Klimatologie, Teil-J, Springer-Verlag (Berlin), 1936, pp. 172 and 253. (Available U. S. Weather Bur. Lib.) 1 table. Brief summary of data on hailstorm frequency, distribution, and damage. Table lists 195 places with monthly and annual days of hail.

D-44. Reya, Oskar: O toči v Dravski banovini v 1936. (On the Hailstorm in Northwest Jugoslavia in 1936). Geografski Vestnik, Ljubljana, Racnik 12, Číslo 13, 1936-1937, pp. 101-114. (Available U. S. Weather Bur. Lib.) 5 charts, 1 table. Summary in German pp. 112-114. Observations at 284 stations show 326 hailstorms for 1936. Five occurrences are analyzed thoroughly and isochronal charts presented for each case.

D-45. Anon.: Some Studies of the Occurrence of Hail. Geographical Rev. (New York), vol. 27, no. 1, Jan. 1937, pp. 151-152. On occurrence of hailstorms in French West Africa from 1921 to 1934.

D-46. Bailland, René: Fondre et grêle dans le départment du Doubs régions privilégiées. (Lightning and Hail in the Favored Region of the Department of Doubs.) La Météorologie (Paris), 3e série, Jan.-Feb. 1937, pp. 16-21. (Available U. S. Weather Bur. Lib.) 3 figures. Coincidence in the occurrence of lightning strikes and hail in the same immediate vicinities of the Doubs region.

D-47. Hrudičks, B.: Die Hagelverhältnisse in Böhmen. (Hail Conditions in Bohemia.) Meteorol. Zeitschr. (Brunswick), Bd. 55, Heft 3, March 1938, pp. 111-112. 1 figure, 9 references. After reviewing the sources of data and early studies on hail distribution in Bohemia (Kreil, 1865), the author presents data for various parts of the country along with a chart showing the probability of hail according to five class intervals ranging from 1 to 4 percent. Extreme maximum probability of 10 percent is in South Bohemia where the thunderstorm frequency is least. In the north where hail damage probability is least, the maximum rainfall amount and thunderstorm frequency prevails.

*D-48. Ramdas, L. A., Satakopan, V., and Gopal Rao, S.: Frequency of Days with Hailstorms in India. Indian Jour. of Agric. Sci. (New Delhi), vol. VIII, Dec. 1938, pp. 787-805. 2 tables, 14 figures. (Available U. S. Dept. Agric. Lib.) The figures and tables showing the frequency of hail in India are based on 38 years of records at the majority of the stations, but the tables are all computed to a 100-year basis.

D-49. Dauzère, Camille, and Bouget, Joseph: Sur la répartition des coups de foundre et des chutes de grêle dans le department des Hautes-Pyrénées. (On the Distribution of Strokes of Lightning and Falls of Hail in the Department of Hautes-Pyrenees.) Comptes Rendus (Paris), tome 208, no. 23, June 5, 1939, pp. 1833-1835. An attempt to show a relation between geologic structure, constitution of the soil, and occurrence of lightning and hail.

*D-50. Anon.: Thunderstorms. UAL Meteorology Circular No. 6, Meteorology Dept., United Air Lines Transport Corp. (Chicago), June 15, 1939, pp. 1-6. A detailed analysis was made of 136 hailstorms where the hailstones were the size of walnuts or larger, between 1931 and 1938. Five tables on hail distribution are included.

D-51. Dauzère, Camille: Sur la répartition géographiques de la foudre et de la grêle dans le département de l'Ariège. (On the Geographic Distribution of Lightning and Hail in the Department of Ariege.) Comptes Rendus (Paris), tome 209, Dec. 11, 1939, pp. 896-897. An attempt to show a relation between geologic structure, soil types, and occurrence of lightning and hail.

1940 - 1950

*D-52. Lemons, Hoyt: Hail in High and Low Latitudes. Bull. Am. Meteorol. Soc., vol. 23, no. 2, Feb. 1942, pp. 61-68. 1 table, 11 references. A discussion of equatorial and polar hailstorms. Includes subtropic area. Cites a number of widely scattered instances (low and high lat.) in which hail fell, with conclusions for each one.

*D-53. Lemons, Hoyt: Hail as a Factor in the Regional Climatology of the United States. Geographical Rev. (New York), vol. XXXII, no. 3, July 1942, pp. 471-475. 17 figures. Time areal distribution; significance of hail; annual, seasonal, and monthly maps of hail distribution. Maps show general patterns of hailstorm distribution and occurrence. Areas of widest hail incidence are most extensively cultivated.

*D-54. Lemons, Hoyt: Hail in American Agriculture. Economic Geography. Clark Univ. (Worcester), vol. 18, no. 4, Oct. 1942, pp. 363-378. 17 figures. Statistics on hail damage and occurrence. Hail distribution in detail for Kansas, Iowa, Michigan, and North Dakota.

*D-55. Lemons, Hoyt: Semimonthly Distribution of Hail in the United States. Monthly Weather Rev., vol. 71, no. 7, July 1943, pp. 115-122. 27 figures. Little text; mostly maps. Twenty-four semimonthly maps show hail distribution and frequency in the United States.

*D-56. Kaster, H. B.: Thunderstorms. UAL Meteorology Circular No. 25, Meteorology Dept., United Air Lines, Inc. (Chicago), March 1, 1944, pp. 2-3. General discussion of thunderstorms and associated weather, and methods used in flying. Includes brief summary on hail frequency.

*D-57. Shands, A. L.: The Hail-Thunderstorm Ratio. Monthly Weather Rev., vol. 72, no. 3, March 1944, pp. 71-74. Gives mostly reasons for the wide variance of hail-thunderstorm ratio throughout the country. Makes reference to charts in "Climate and Man." Concludes that climatic summaries seem to indicate that hail usually occurred in a state, on more than 20 percent of the days on which there were thunderstorms. The 25-year period from 1915 to 1940 was used to determine how many days there were thunderstorms in the state of Iowa and in the Maryland - Delaware - District of Columbia area.

D-58. Anon.: Estudios Superiores, Sección de Investigaciones Meteorológicas. Observación de la frecuencia e intensidad del granizo en todo el territorio de la Republica. (Observation of the Frequency and Intensity of Hail in the Entire Republic.) Boletin de Meteorológia (Montevideo), Año 2, no. 2, 1944, pp. 9-10. (Available Lib. of Congress.)

D-59. Morandi, Luis: El Granizo en Juestro Clima. (Hail in Our Climate.) Revista Meteorológica (Montevideo), Año 4, no. 13, Jan. 1945, pp. 60-62. (Available U. S. Weather Bur. Lib.) Tables. Statistics based on 8 years observations of hail in the Prado (Montevideo) and 31 years in Villa Colón. Table gives average annual frequency of hail for 12 departments of Uruguay. Details of hail size.

D-60. Bergeiro, José M.: Frequencia e intensidad del granizo en el Uruguay. (Frequency and Intensity of Hail in Uruguay.) Revista Meteorológica (Montevideo), Año 4, no. 16, Oct. 1945, pp. 276-286. (Available U. S. Weather Bur. Lib.) 5 charts, 1 table. A study covering the decade from 1934 to 1943. Includes survey of hail size distribution.

D-61. Ruby, F.: La grêle dans le département du Rhône. (Hail in the Department of Rhone.) Le climat de Lyon et de la région Lyonnaise, M. Pierty, ed., Editions Gartier (Lyon), 1946, pp. 136-139. (Available U. S. Weather Bur. Lib.) Table shows total number of hailstorms by months for 25 years.

D-62. Depeyre, G. P.: Statistique des orages à grêle ayant atteint la Station du Sol. Commune de Montfermier (Tarn-et-Garonne) de 1901 a 1946. (Statistics on Hailstorms Which Reached the "Station du Sol" Municipality of Montfermie (Tarn-et-Garonne) from 1901 to 1946.) La Météorolgie (Paris), 4e série, no. 5, Jan.-March 1947, pp. 56-57. A brief statistical record of all storms with hail recorded in the vicinity in that period.

D-63. Sutton, L. J.: Snow and Hail in Egypt. Weather (London), vol. 2, no. 7, July 1947, pp. 218-221. 1 map. Noted briefly instances of hail in Egypt in 1907, 1923, 1932, and 1937. Severe hailstorms usually occurred during thunderstorms in October or November.

D-64. Aujesky, László: Jégeső gyakoriság és valószínűseg Budapesten, 1871-1945. (Hail Frequency and Hail Probability in Budapest, 1871-1945.) Orszagos Meteorologiai es Foldmagnessegi Intezet (Budapest), 1947, 22 pp. (Available U. S. Weather Bur. Lib.) 13 tables, 15 references. Summary in English, p. 26. Hailstorms are discussed from different points of view for the 105 years: 1781-1792, 1841-1848, and 1861-1945. Tables give values of yearly trend of hail occurrences and hail frequency for decades during the period from April to August.

*D-65. Hydrometeorological Section: Thunderstorm Rainfall. Hydrometeorological Rep. No. 5, U. S. Weather Bur. (Washington), 1947, pt. 1, pp. 144-175, pt. 2, figs. 69-77 and 83. Part I contains text and tables; part 2 contains figures and charts and is bound separately. Tables show hail-day data from the 40 years of record, 1904-1943, and give a detailed comparison of the thunderstorm and hail-distribution patterns.

*D-66. Anon.: A Report on Thunderstorm Conditions Affecting Flight Operations. Tech. Paper No. 7, U. S. Weather Bur. (Washington), April 1948, pp. 13, 21, and 22. Few instances of hail in Florida and Ohio thunderstorms. Hail seldom found at more than one or two levels in the same storm. Tables show frequency and percentage distribution on various hail intensities at a given altitude. Project carried out in regions considerably removed from area of maximum occurrence of hail at the surface.

*D-67. Visher, Stephen S.: Thunderstorms. Scientific Monthly (Washington), vol. 66, no. 4, April 1948, pp. 335-340. 8 maps. Includes one map giving the month of maximum hail in various sections of the United States.

D-68. Champion, Donald L.: The Seasonal Distribution of Hail in Great Britain. Weather (London), vol. 3, no. 7, July 1948, pp. 201-205. 4 figures, 1 plate, 1 table. Analysis and compilation of records made throughout Britain for 10 years (1937-1946) indicate greater frequency of hail at coastal stations than in interior, although greater incidence of thunderstorms in interior places. Inverse relation to thunderstorms with maximum in summer and minimum in midwinter. Conclusion is that hail is a convergence phenomenon along coast line, whereas thunderstorms are more often of convective origin.

D-69. Anon.: Grady w Polsce, 1947. (Hail in Poland, 1947.) Prace, Zeszyt 3 (Reports, pt. 3), Panstwowy Instytut Hydrologiczno-Meteorologiczny (Warsaw), 1948, 110 pp. (Available U. S. Weather Bur. Lib.) 4 tables, 6 maps. Shows concerted effort to make hail report. Extensively tabulated observations of hail taken throughout Poland in 1947. More statistical than meteorological.

D-70. Philippson, Alfred: Das Klima Griechenlands. (The Climate of Greece.) Ferd. Dummlers, Bonn, 1948, pp. 120-121. (Available Harvard Univ., Blue Hill Observatory Lib.) 1 table. Reference is made to annual hail frequency data for 26 stations, and monthly frequency for 10 stations. Range is very great; seven days a year in Crete to 1 day a year or less at Lamia.

*D-71. Braham, Roscoe R., and Pope, Fred W.: Further Studies of Thunderstorm Conditions Affecting Flight Operations: Turbulence. Tech. Rep. 105-39, Headquarters Air Weather Service (Washington), March 1949, 31 pp. 8 tables, 9 figures, 15 references. Few instances of hail in Florida or Ohio thunderstorms. Hail seldom found at more than one or two levels in the same storm. Tables show frequency and percentage distribution of various hail intensities at a given altitude.

*D-72. Harrison, H. T., and Beckwith, W. B.: A Re-examination of Hail Patterns over Western United States. UAL Meteorology Circular No. 35, Meteorology Dept. United Air Lines, Inc. (Chicago), March 1950, 27 pp., 15 figures, 17 references. Geographical distribution of hail; damage to aircraft aloft; local observations of hail and synoptic patterns for hail at Denver; problems of hail forecasting; pilots' responsibility for avoiding hail.

E.- HAIL FORMATION THEORIES AND FORECASTING

1822 - 1849

E-1. Anon.: On the Formation of Hail. Phil. Mag. (London), vol. 59, 1822, pp. 93-97.

E-2. Hallowell, Benjamin: On the Cause of Hail during Warm Weather. Am. Jour. Sci. (New Haven), First ser., vol. 15, 1829, pp. 361-362.

E-3. Olmstead, Denison: On the Phenomena and Causes of Hailstorms. Am. Jour. Sci. (New Haven), First ser., vol. 18, 1830, pp. 1-11. 1 graph.

E-4. Perevoschtchikoff: Formation of Hail. Am. Jour. Sci. (New Haven), First ser., vol. 19, 1831, pp. 396-397.

E-5. Espy, James P.: Theory of Hail. Essays on Meteorology, No. 1 and 2. Jour. Franklin Inst. (Philadelphia), New Ser., vol. 17, April 1836, pp. 240-246, 309-316.

E-6. Rive, M. de la: On the Formation of Hail. Jour. Franklin Inst. (Philadelphia), New ser., vol. 21, March 1838, pp. 201-209; comments, April 1838, p. 280.

1850 - 1899

E-7. Bowditch, W. R.: On the Formation of Hail, as Illustrated by the Local Storms. Rep. British Assoc. (London), pt. 2, 1858, pp. 35-36.

*E-8. Smith, Spencer: An Hypothesis Concerning the Formation of Hail. Trans. Acad. Sci. St. Louis, vol. I, 1856-1860, pp. 297-300. (Available Lib. of Congress.) The theory is advanced that the passage of a current of electricity through the atmosphere would cause a rapid expansion and thus cause cooling. The small hail first formed, being tossed about in this cold current, would, on coming in contact with each other, be quickly congealed together, thus deriving the aggregated form.

E-9. Reinsch: Origin of Hail. Jour. Franklin Inst. (Philadelphia), Third ser., vol. 62, Aug. 1871, pp. 80-81.

E-10. Reynolds, Osborne: On the Manner in Which Raindrops and Hailstones Are Formed. Memoirs Literary and Phil. Soc. (Manchester), vol. 6, 1875-1878, pp. 48-60; Proc. Literary and Phil. Soc. (Manchester), vol. 16, 1876-1877, pp. 23-24. Also in Nature (London), vol. 15, 1876, pp. 163-165, and Popular Science Monthly, Am. Assoc. Advancement Sci. (Washington), vol. 10, March 1877, pp. 522-527.

E-11. Reynolds, Osborne: On the Formation of Hailstones, Raindrops, and Snowflakes. Memoirs Literary and Phil. Soc. (Manchester), vol. 6, 1875-1878, pp. 161-170; Proc. Literary and Phil. Soc. (Manchester), vol. 17, 1877-1878, pp. 15-24. Also in La Nature (Paris), vol. 17, 1877-1878, pp. 207-209.

E-12. Schwaab, W.: Die Hagel-Theorien; alterer und neuerer Zeit, deren Nachweis in der Literatur nebst theilweiser kritischer Beleuchtung. (Hail Theories; Earlier and Modern Times, References to the Literature As Well As Critical Comments.) Verlag der E. Hühn'schen Buchhandlung (Cassel), 1878, 35 pp. (Available U. S. Weather Bur. Lib.)

E-13. Oltramare, M. G.: Formation of Hail. Jour. Franklin Inst. (Philadelphia), Third ser., vol. 78, Aug. 1879, p. 104.

E-14. Oliver, J. A. W.: The Theory of Hailstorms. Nature (London), vol. 20, 1879, p. 603.

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E-21. Very, Frank W.: Cloud Phenomena Attending Hailstorms. Monthly Weather Rev., vol. 22, no. 7, July 1894, pp. 292-293.

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E-31. Hackey, H. B.: The Rotation of Melting Ice Suspended in Benzine. Jour. Franklin Inst. (Philadelphia), vol. 197, no. 6, June 1924, pp. 825-827.

*E-32. Humphreys, W. J.: The Uprush of Air Necessary to Sustain the Hailstone, Monthly Weather Rev., vol. 56, no. 8, Aug. 1928, p. 314. Supports the theory that updrafts are necessary for the production of large hailstones. Table based on wind-tunnel experiments shows speed of updrafts necessary to sustain various sizes of hailstones.

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E-39. Kunze, G.: Sind Hagelschläge Luftelektrisch Bedingt? (Do Hailstorms Depend on Atmospheric Electricity?) Meteorol. Zeitschr. (Brunswick), Bd. 53, Heft 1, Jan. 1936, pp. 32-33. 2 figures, 4 references. Correlation found between days with good short-wave radio (10m) transmission and days without hail. The conclusion is that good radio reception occurs when subsiding air masses prevail; a condition unfavorable for hail occurrence; and that poor reception occurs where air masses with convective activity prevail.

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E-43. Kunze, Gerhard: Hagelhäufigkeit und Kurzellenausbreitung. (Hail Frequency and Short Wave Propagation.) Meteorol. Zeitschr. (Brunswick), Bd. 54, Heft 1, Jan. 1937, pp. 27-28. A rebuttal to the article by Stoye, defending the author's previous article (E-42) about the $5\frac{1}{2}$-day periodicity in the occurrence of hail and short-wave reception.

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E-47. Frey, H.: Zur Entstehung des Hagels. (Formation of Hail.) Beiträge zur Geophysik (Leipzig), Bd. 50, Heft 2-4, 1937, pp. 216-222. (Available Lib. of Congress.) 3 figures, 19 references. By observation of hailstones, an analysis of conditions favorable for the formation of hail and the internal structure of the cloud was conducted. For producing hail a labile air layer, supersaturated with water vapor and with strongly supercooled water drops at about 4000 meters is assumed. Tiny drops are formed by the falling in of snowflakes, and with emission of latent heat of crystallization they are shot upwards. A premature disturbance of the labile equilibrium opposes the formation of hail.

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E-53. Chalmers, J. A., and Little, E. W. R.: Electric Charge on Soft Hail. Nature (London), vol. 143, no. 3615, Feb. 11, 1939, p. 244. Record of a larger precipitation current than had ever been observed before.

E-54. Rossmann, F.: Blitz und Hagel (Über die Elektrische Natur des Gewitters). (Lightning and Hail (On the Electrical Nature of Thunderstorms.)) Meteorol. Zeitschr, (Brunswick), Bd. 56, Heft 10, Oct. 1939, pp. 372-378. 2 figures, 17 references. Based on 3 years of observations at Feldberg (Schwarswald) and on reports from flights through thunderstorms and rainshower clouds, the author presents a schematic picture of the structure of the two types of cumulus clouds (water clouds and ice clouds), showing the zones where ice particles, snow, graupel, hail, melting snow, and rain occur, and the electric field in the vicinity of the cloud. A theory on the relation of hail to lightning is presented, with numerous quotations from literature dating back to the 18th Century. Hail and lightning are less frequent when the zero isotherm is high, than (as in Aug. to May) when it is low, and also less frequent in the tropics than the temperate zone, and in midday than at night.

1940 - 1950

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*E-58. Humphreys, W. J.: Physics of the Air. Third ed., McGraw-Hill Book Co., Inc. (New York), 1940, pp. 359-360. Discussion of the formation of hail, sizes and shapes.

E-59. Brunt, David: Weather Study. The Ronald Press Co. (New York), 1942, pp. 126-127. Brief, simple, step-by-step description of the formation of hailstones, with schematic diagram.

*E-60. Byers, Horace Robert: General Meteorology. McGraw-Hill Book Co., Inc. (New York), 1944, pp. 126, 163-164, 565-566, and 578-581. Explains briefly the multiple incursion and long-fall theories of hail formation. Explanation for exploding hailstones. Includes maps of average annual number of days with hail.

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E-63. Newman, B. W.: Phenomenal Hailstorm with Thunderstorm, Sydney, 1st January, 1947. Weather Development and Research Bulletin, No. 8, R.A.A.F. (Melbourne), July 1947, pp. 23-38; comments pp. 39-41. (Available U. S. Weather Bur. Lib.) 7 figures, including synoptic chart and three adiabatic charts. Path of storm outlined, detailed description of meteorological changes with data, data from area where storm originated. Lists primary predictions that would have been necessary for a more accurate forecast.

*E-64. Gaviola, E., and Alsina Fuertes, F.: Hail Formation, Vertical Currents, and Icing of Aircraft. Jour. Meteorology, vol. 4, no. 4, Aug. 1947, pp. 116-120; comments by Chester W. Newton, vol. 4, no. 6, Dec. 1947, pp. 205-206. 1 table, 3 equations, 11 references. Critical examination of theory that hail formation depends on strong ascending currents. Outlines a tentative description of the growth of large hailstones; no evidence that vertical currents exist whose speed could compare with that of falling hailstones.

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*E-66. Jude, F. W.: Severe Storms of July 2-4, 1946. Meteorol. Mag. (London), vol. 77, no. 913, July 1948, pp. 153-160. 6 figures. A discussion of the storms that swept many parts of England, including the extent of damage, synoptic situation, and upper-air data.

*E-67. Horton, Robert E.: Convectional Vortex Rings - Hail. Trans. Am. Geophysics Union (Washington), vol. 30, no. 1, Feb. 1949, pp. 29-45. 9 figures, 4 tables, 22 equations, 21 references. Comprehensive treatment, with theoretical and practical aspects, of hailstorms that occur in conjunction with ring-vortex storms. Description of vortex-ring clouds from Mears, Creighton, and others. Statements verified by experiment using smoke-box apparatus. Characteristics of hail, giving illustrations from Arenberg, Ellison, Russell, and others. In the conclusions it is stated that hail formed in ring vortices is likely to be of maximum size, and relatively uniform in size and internal structure.

*E-68. Workman, E. J., and Reynolds, S. E.: Some Electrical Properties of Water. Symposium on Tropospheric Wave Propagation, U. S. Navy Electronics Lab. (San Diego, Calif.) July 25-29, 1949, pp. 118-121. A review of thunderstorm development characteristics, and the results of laboratory experiments on the freezing of dilute aqueous solutions.

*E-69. Ludlam, F. H.: The Composition of Coagulation-Elements in Cumulonimbus. Quarterly Jour. Roy. Meteorol. Soc., vol. 76, no. 327, Jan. 1950, pp. 52-58. 3 figures, 1 table, 7 references. Calculations are made from which it appears that the rate of loss of heat from ice particles growing by coagulation in dense supercooled clouds may be insufficient to allow all the acquired water to freeze. The larger coagulation-elements within cumulonimbus clouds may therefore have liquid skins at levels where the temperature has fallen to -20° or -30° C. The effect may be important in the production of ice nuclei by "splinter" formation and in the generation of thunderstorm electricity.

*E-70. Workman, E. J., and Reynolds, S. E.: Electrical Phenomena Occurring during the Freezing of Dilute Aqueous Solutions and Their Possible Relationship to Thunderstorm Electricity. Physical Rev. (New York), vol. 78, no. 3, May 1, 1950, pp. 254-259. The discovery of an electrical effect accompanying the orderly freezing of dilute aqueous solutions is reported. Potential differences as great as 230 volts are measured across the water-ice interface during the freezing process. Application of this effect to the formation of hail and thunderstorm electricity is discussed.

F.- HAIL DAMAGE AND PREVENTION

1826 - 1849

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F-2. Murray, John: On the Paragrele or Protector from Hail. Edinburgh New Phil. Jour., vol. 3, 1827, pp. 103-107.

F-3. Anon.: On the Efficacy of Paragreles. Am. Jour. Sci. (New Haven), First ser., vol. 14, 1828, pp. 37-40.

F-4. Anon.: Indian Superstition. Scientific American (New York), vol. 3, May 20, 1848, p. 275. Destruction of wild geese by hail.

1850 - 1899

F-5. Anon.: Protection against Hail. Am. Jour. Sci. (New Haven), Second ser., vol. 18, 1854, pp. 432-433.

F-6. Rowell, G. A.: On Forests and Hailstorms. Builder (London), vol. 43, 1882, p. 730.

F-7. Anon.: Preserving Young Plants from Hailstorms. Scientific American (New York), Second ser., vol. 76, June 12, 1897, p. 378.

1900 - 1919

F-8. Hilgrad, Eugene W.: Prevention of Hail. Science (Washington), New ser., vol. 11, Jan. 26, 1900, p. 153.

F-9. Sigaux, J.: Hail Showers and Cannonades. Revue Scientif (Paris), tome 14, Oct. 13, 1900, pp. 461-464. A report on the First Conference on Weather Shooting held in 1899. There were at this time 16,000 hail reporting stations in Italy. The guns used in the prevention of hail were mounted perpendicularly. Since the hail generally moves from the southwest, the guns were discharged in that direction first. Discharges were made twice each minute.

F-10. Abbe, Cleveland, ed.: Bombarding Hail Clouds. Monthly Weather Rev., vol. 28, no. 12, Dec. 1900, pp. 542-543.

F-11. Pernter, J. M.: Damage by Hail in Spite of Cannonading. Monthly Weather Rev., vol. 29, no. 3, March 1901, p. 117. From Meteorol. Zeitschr. (Brunswick), Bd. 18, March 1901, p. 135.

F-12. Abbe, Cleveland, ed.: Bombardment of Hailstorms. Monthly Weather Rev., vol. 29, no. 4, April 1901, p. 176. Method for the prevention of hail.

F-13. Shaw, W. N.: Hailstorm Artillery. Nature (London), vol. 64, June 13, 1901, pp. 159-161. Gives an account of the methods used in the prevention of hail by the use of cannon. Shows how their use has spread from Italy to other parts of Europe in recent years.

F-14. Ward, Robert DeCourcy: Hail Prevention by Cannonading. Science (Washington), New ser., vol. 14, Dec. 13, 1901, p. 938.

F-15. Abbe, Clevelend, ed.: The Third International Congress on Hail Shooting. Monthly Weather Rev., vol. 30, no. 1, Jan. 1902, pp. 33-35.

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F-18. Angot, Alfred: Bombarding against Hail. Monthly Weather Rev., vol. 31, no. 1, Jan. 1903, p. 30. Describes hail prevention by cannonading in Italy.

F-19. Marangoni, C.: Dispersal of Hail-Clouds. Rivista Scientific-Industriale (Florence), tomo 36, Feb. 29, 1904, pp. 25-31. An account of successful experiments in Italy with large conical cannons in which acetylene-air mixture is exploded.

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F-22. Scharf, Edmund: On the Effects of Hail on Crops. Monthly Weather Rev., vol. 35, no. 2, Feb. 1907, p. 71. Hail damage in Germany and value of hail insurance in Europe.

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F-24. Phillips, Frank J.: Hail Injury of Forest Trees. Trans. Acad. Sci. (St. Louis), vol. 19, no. 3, March 10, 1910, pp. 49-56. Includes data to show that the midwest is the best field for investigation. Plates show injury to twigs of various types.

F-25. Angot, Alfred (Rowena E. Edwards, trans.): Electric Paragreles. Monthly Weather Rev., vol. 42, no. 3, March 1914, pp. 166-167.

F-26. Anon.: Guns That Protect Crops from the Ravages of Hailstorms. Scientific American (New York), Second ser., vol. 114, May 1916, p. 557. Illustrated.

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F-28. Flora, S. C., and Bush, C. L.: Damage by Hail in Kansas. Monthly Weather Rev., vol. 45, no. 7, July 1917, pp. 359-361. 1 table, 2 maps. Hail damage in Kansas is analyzed by counties.

1920 - 1929

F-29. Holmes, J. W.: Damage to Forests by Hail in North Carolina. Monthly Weather Rev., vol. 49, no. 6, June 1921, p. 333. 1 graph. Hailstorm in Anson County on April 28, 1921. About 10 percent of foliage left on forested area.

F-30. Anon.: The Hailrods of France. Tycos-Rochester, vol. 14, July 1924, p. 36. Illustrated.

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F-32. Anon.: Hail Insurance Pays - "Hailrods" Are Worthless. Bull. Am. Meteorol. Soc., vol. 5, no. 10, Oct. 1924, p. 146.

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F-34. Flora, S. D.: Hail Hazard. Tycos-Rochester, vol. 17, Jan. 1927, pp. 12-13. Illustrated.

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*F-36. Flora, S. D.: The Widespread Menace of Hail. Monthly Weather Rev., vol. 56, no. 1, Jan. 1928, p. 17. Brief summary of hail occurrence and damage for 1927.

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F-40. Stout, Gilbert L.: Severe Hail Injury to Trees and Shrubs. Science (Washington), New ser., vol. 71, Feb. 14, 1930, pp. 187-188.

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F-45. Anon.: Fighting the Hailstorm. Tycos-Rochester, vol. 22, July 1932, p. 106. Illustrated.

F-46. Flora, Snowden D.: Destructive Force of Hail. Tycos-Rochester, vol. 22, no. 4, Oct. 1932, pp. 129-130. 3 figures.

F-47. Gates, William H.: Hailstone Damage to Birds. Science (Washington), New ser., vol. 78, Sept. 22, 1933, p. 263.

F-48. Barron, W. E.: Heavy Hail Losses in Western Canada. Bull. Am. Meteorol. Soc., vol. 15, no. 12, Dec. 1934, pp. 308-309. Crop loss in Saskatchewan from beginning of 1934 to latter part of July was estimated at $2,500,000.

F-49. Eldridge, John C.: The Effect of Injury in Imitation of Hail Damage on the Development of the Corn Plant. Research Bull. No. 185, Iowa Agriculture Experiment Station, 1935, 61 pp. Illustrated.

F-50. Hummel, Alfred: Die Beurteilung von Hagelschäden. (The Valuation of Hail Damage.) Reichsnährstand Verlags (Berlin), 1936, 49 pp. (Available Lib. of Congress.) 41 figures. Illustrations and descriptions of types of hail damage to various grains. Suggests precautions to be taken in evaluating damage in respect to insurance.

F-51. Hrudička, B.: Über Hagelschlag in Mähten-Schlesien. (On Hail Damage in Moravian Silesia.) Meteorol. Zeitschr. (Brunswick), Bd. 54, Heft 7, July 1937, pp. 265-267. 2 figures. Based on records of hail damage for the years 1926-1935, the frequency of hail in various parts of Moravian Silesia, and the hail damage "quotient" or probability is calculated and shown in two charts.

F-52. Kincer, Joseph Burton: The National Loss from Windstorms, Hail, Floods, Drought and Other Weather Vagaries. Bull. Am. Meteorol. Soc., vol. 18, no. 9, Sept. 1937, pp. 304-306. Gives percentage of wheat crop lost in one state in 1 year; value of loss over a 12-year period in another; loss in bushels of major crops over the country over a 17-year period.

F-53. Piersig, W.: Gewittertätigkeit und Hagelwetter in Südbayern, am 27. Juli 1936. (Thunderstorm Activity and Hailstorms in South Bavaria on July 27, 1936.) Meteorol. Zeitschr. (Brunswick), Bd. 55, Heft 2, Feb. 1938, pp. 48-54; discussion by Franz Zimmer, Bd. 55, Heft 4, April 1938, p. 153. 8 figures, 3 tables, 8 references. Synoptic and upper air analyses of conditions before and during an outbreak of cold air into Bavaria, which resulted in severe thunderstorms, heavy rain, and widespread hail damage along a strip 15 kilometers wide and 180 kilometers long. Crops were 70 to 100 percent destroyed. This storm was not the most severe in Germany - (the one of July 8, 1927, in the East Erzgebirge killed 146 people).

*F-54. Brachet, Charles: Pour lutter contre les chutes de grêle, utilisez l'avion. (Combatting Hail Occurrence by Use of Airplanes.) La Science et la Vie (Parios), tome LIII, Nr. 248, Feb. 1938, pp. 101-108.

F-55. Hummel, Alfred: Wissenschaftliche Grundlagen zur Schätzung von Hagelschäden; eine leicht verstandliche Unleitung für den praktischen Schätzer. (Scientific Basis for Estimate of Hail Damage; An Easily Understood Guide for the Practical Appraiser.) Reichsnährstand Verlags (Berlin), 1938, 52 pp. (Available Lib. of Congress.) 47 figures. Detailed discussion of the effect of hail damage on the growing process of plants, particularly grain. Illustrations show effect of different types of damage.

F-56. Schlumberger, Otto: Hagelversicherung und Schadensbeurteilung beim Körnemais. (Hail Insurance and Estimation of Damage to Corn.) Paul Parey (Berlin), 1938, 19 pp. (Available U. S. Dept. of Agric. Lib.) 6 figures.

F-57. Allix, André: L'étude de la grêle par avion et le système de défense du Beaujolais. (The Study of Hail by Airplane and the System of Defense of Beaujolais.) Revue pour l'Étude des Calamités (Geneva), tome 2, no. 5, March-April 1939, pp. 89-100. (Available U. S. Weather Bur. Lib.) 4 figures. Explanation of hail defense system used in Beaujolais where damage to vineyards has been extensive. Bombs are dropped on portion of thundercloud where hail is forming, and these are supplemented by mobile ground batteries. Success is claimed.

1940 - 1950

*F-58. Jenkins, Merle T.: Influence of Climate and Weather on the Growth of Corn. Climate and Man. Yearbook of Agriculture, U. S. Dept. of Agric., 1941, pp. 314 and 730. Includes a hail map and a very brief discussion of hail damage to crops.

F-59. Darbre, Pierre: Le problème de la grêle-etat actuel. (The Problem of Hail-Present Status.) Société Vaudoise des Sciences Naturalles (Lausanne), tome 62, no. 260, July 1943, pp. 261-272. (Available U. S. Lib. of Congress.) 3 figures, 3 tables.

*F-60. Anon.: Combined Report of Trip to Denver, ATA Conference. Flight Rep. No. 35, ANTC Branch, Flight Engineering, American Airlines System (New York), July 15-20, 1946, pp. 2, 3, and 5. Radar search on flat, sandy terrain, and radar detection of thunderstorms, rain, and hail. Comparison of cloud and rain echos with terrain echos.

*F-61. Hotz, Robert: All-Weather Flying Center Develops New Operational Aids. Aviation Week, vol. 47, no. 17, Oct. 27, 1947, pp. 11-12. Progress report on Air Force research program at Wilmington, Ohio, indicates benefits for civilian aviation. Includes pilot's report of F-61 which encountered hail.

*F-62. Anon.: Some Preliminary Data Affecting Design Criteria for Nose Radomes with Respect to Hail Penetration. Tech. Note. No. 2, ANTC Branch, Flight Engineering, American Airlines System (New York), Jan. 14, 1948, 4 pp., 3 photos. Includes pilot's report of DC-6 which encountered hail on Sept. 14, 1947 over north-eastern Mexico at 18,000 feet, resulting in severe damage to the aircraft.

*F-63. Anon.: Flying around and through Thunderstorms Using Airborne Radar. Flight Test Rep. No. 58, ANTC Branch, Flight Engineering, American Airlines System (New York), Feb. 26, 1948, pp. 2, 10, 14, 16, 20, and 21. Shows pictures of thunderstorm clouds (when rain and hail were encountered) with accompanying pictures of the radar echos on the PPI scope.

*F-64. Anon.: A Violent Hailstorm in Oxfordshire on May 11, 1945. Meteorol. Mag. (London), vol. 77, no. 909, March 1948, p. 65. Description of aircraft accident with three pictures showing damage.

*F-65. Anon.: Information on Second Case of Hail Damage to DC-6 Aircraft NC-90733. Tech. Note No. 3, ANTC Branch, Flight Engineering, American Airlines System (New York), June 4, 1948, 2 pp. Pilot's report on DC-6 which encountered hail on May 2, 1948 over eastern Tennessee at 19,000 feet, resulting in severe damage to the aircraft.

*F-66. Anon.: Information on Fifth Case of Hail Damage to DC-6 Aircraft (NC-90702). Tech. Note No. 5, ANTC Branch, Flight Engineering, American Airlines System (New York), July 26, 1948, 2 pp. DC-6 encountered hail for 10 minutes at about 14,000 feet. Only minor damage resulted because of reduced airspeed.

*F-67. Press, H., and Binckley, E. T.: A Preliminary Evaluation of the Use of Ground Radar for the Avoidance of Turbulent Clouds. NACA TN 1684, 1948. 13 pp., 4 figures, 2 tables. Contains an analysis of gust data obtained by aircraft flight within convective-type thunderstorms over Florida.

F-68. Morris, H. E.: Simulated Hail Damage to Sugar Beets. Proceedings of Fifth General Meeting, Am. Soc. of Sugar Beet Technologists, 1948, pp. 358-362. (Available U. S. Dep. of Agric. Lib.) 3 tables.

F-69. Anon.: Daños producidos por el padrisco y medios para evitarlos. (Damage Produced by Hail and Methods for Preventing It.) Calendario Meteoro-Fenológica 1949, Seccion de Climatologia, Servicio Meteorológica Nacional (Madrid), 1948, pp. 104-114. (Available U. S. Weather Bur. Lib.) 3 figures.

*F-70. Roth, Richard J.: Crop-Hail Insurance in the United States. Bull. Am. Meteorol. Soc., vol. 30, no. 2, Feb. 1949, pp. 56-58. Review of the activity of the Crop-Hail Insurance Actuarial Association and its meteorological-statistical research program. Method of collecting statistical information, determination of crop-hail insurance rates, and manner of adjustment in case of damage.

F-71. Capitanelli, Ricardo G.: El Problema General del Granizo y Pedrisco, Particularmente en Mendoza. (The General Problem of Small and Large Hailstones, Particularly in Mendoza.) Boletin de Estudios Geograficas (Mendoza), vol. 1, no. 2, first quarter 1949, pp. 53-66. (Available Lib. of Congress.) 2 tables. Between 1929 and 1948, one-fourth of damage to vineyards by weather disasters was caused by hail. Methods of hail protection, negative results. One table gives percentage of damage to vineyards from all causes and one for damage from hail only.

*F-72. Anon.: Report of Impact Test on Metal Wing Sections and Propeller Dome with Artificial Hailstones. Memorandum Rep., Aircraft Development Div., Structures Section, CAA Tech. Development Experimental Station (Indianapolis), May 1949, 12 pp., 10 figures. Hailstones less than 0.75 inch in diameter caused no damage to DC-6 and DC-3 aircraft wing sections at speeds between 200 and 300 miles per hour. Pictures show extent of damage by hailstones of 0.75, 1.25, and 1.88 inches in diameter.

*F-73. Anon.: Hail Damage to Simulated DC-6 and Convair Leading Edges under Laboratory Conditions and Development of a Suitable Hail Catcher. Tech. Note No. 10, Operational Development Branch, Flight Engineering, American Airlines System (New York), May 3, 1949, 17 pp. (including a 6 page supplement). 4 graphs, 2 tables; 6 figures in supplement. Description and results of hail impact test of metal wing sections carried out by CAA Tech. Development Experimental Station.

*F-74. Anon.: Description of Circuitry for Erasing Video Signals above a Selected Threshold Level and a Flap Attenuator for Automatically Measuring Its Performance When Connected to the Output of an Airborne Radar. Tech. Note No. 12, Operational Development Branch, Flight Engineering, American Airlines System (New York), May 23, 1949, pp. 1-3. Includes two graphs on the reflectivity of radio waves with respect to hail diameters and rainfall rate.

*F-75. Armstrong, L. W.: Information Concerning Hail Damage to DC-6 Aircraft NC-90720. Tech. Note No. 13, Operational Development Branch, Flight Engineering, American Airlines System (New York), Sept. 6, 1949, 7 pp. 8 photos. Pilot's report and discussion of DC-6 which encountered hail on May 25, 1948 over southwest Texas at 16,000 feet, resulting in severe damage to the aircraft.

*F-76. Ayer, R. W., White, F. C., and Armstrong, L. W.: The Development of an Airborne Radar Method of Avoiding Severe Turbulence and Heavy Precipitation in the Precipitation Areas of Thunderstorms and Line Squalls. Final Rep. on Task No. 1 of Navy BuAer Contract NO a(s)-9006, Operational Development Branch, Flight Engineering, American Airlines System (New York), Sept. 15, 1949, 35 pp. 15 figures. Only small hail was encountered during the test flights made on this project. Description is given of the hail encountered and the pilot's reaction. Pictures of the hail catcher are included. Hail fight avoidance possibilities are discussed.

*F-77. Richards, Leverett G.: They Really Do Make Rain. Country Gentelman (Philadelphia), vol. 120, no. 7, July 1950, pp. 19, 60, and 61. Also condensed form in the Readers Digest (Pleasantville), vol. 57, no. 339, July 1950, pp. 63-67. Description of the widespread interest in artificial rain making and the successful results of several independent groups in the United States and Hawaii. Hail control is also explained and illustrated by the activities of the Rogue River Valley Traffic Association in southern Oregon.

G.- RELATED SUBJECTS

1784

G-1. Franklin, Benjamin: Meteorological Imaginations and Conjectures. Memoirs Phil. Soc. (Manchester), vol. 2, 1784, pp. 357-361. Also in: Works. vol. 2, 8vo., London, 1806, pp. 66-69.

1800 - 1899

G-2. Murray, John: A Treatise on Atmospherical Electricity; Including Lightning Rods and Paragreles. 8vo., London, 1828.

G-3. Rigaud, S. P.: Notice of the Occurrence on a Stone Wall of a Remarkable Deposition of Ice. Phil. Mag. (London), vol. 2, 1833, p. 190.

G-4. Nash, W. C.: Notes on the Unusual Heat and Great Dryness of the Atmosphere on May 19th, 1868; and on the Remarkable Thunderstorms of May 29th, 1868, as Observed at Greenwich. Proc. British Meteorol. Soc. (London), vol. 4, 1867-1869, pp. 196-198.

G-5. Buchan, Alexander: The Annual Periods of Thunder (with Lightning), Lightning (Only), Hail and Snow at Oxford. Proc. Roy. Soc. Edinburgh, vol. 9, 1875-1878, pp. 135-136.

G-6. Dalhear, A. E.: Matter, Action, and Motion. Lathrop, Lee and Shepard Co. (Boston), 1894.

G-7. Risteen, A. D.: Molecules and the Molecular Theory. Ginn & Co. (Boston), 1898, pp. 174-175.

G-8. Karpinsky: Cosmic Dust in Hail. Jour. Franklin Inst. (Philadelphia), vol. 117, Feb. 1899, pp. 168-169.

1900 - 1929

G-9. Newcomb, Simon: Further Explanations. Monthly Weather Rev., vol. 30, no. 3, March 1902, pp. 127-129. Discussion on the cause of rain, thunderstorms, and winds.

G-10. Wegener, A.: Thermodynamik der Atmosphare (Leipzig), 1911, pp. 94 and 291.

*G-11. Brooks, C. F.: The Nature of Sleet and How It Is Formed. Monthly Weather Rev., vol. 48, no. 2, Feb. 1920, p. 69. Description of sleet, and its formation; only mentions hail as differing from sleet.

G-12. Kassner, C.: Das Reich der Walken und Niederschlaege. (The Domain of Clouds and Precipitation). Velag Quelle und Meyer (Leipzig), 1926.

G-13. Crichton, J.: A Complete Cloud Vortex. Meteorol. Mag. (London), vol. 63, Oct. 1928, pp. 212-214.

1930 - 1939

*G-14. Lange, K. O. (J. Vanier, trans.): Measurements of Vertical Air Currents in the Atmosphere. NACA TM 648, 1931, 9 pp, 9 figures. Extensive research was conducted with balloons, sailplanes, and light airplanes at the Research Institute of the Rhon-Rossitten Society of Germany. The results reveal that the vertical velocities of the air are primarily dependent on the vertical temperature distribution. Effect of local terrain, sky conditions, wind, and so forth, are discussed.

G-15. Albrecht, F.: Ablagerung von Staub aus Ströemender Luft. (Deposition of Dust from Flowing Air.) Physikalische Zeitschr. (Leipzig), Bd. 32, 1931, pp. 48-56.

G-16. Wegener, A., and Wegener, K.: Vorlesungen über Physik der Atmosphäre. Verlag Ambr. Barth (Leipzig), 1935.

*G-17. McNeal, Don: Ice Formation in the Atmosphere. Jour. Aero. Sci. (New York), vol. 4, Jan. 1937, 14 pp. Discusses, (a) the condensation of water vapor, (b) the existence of undercooled water, and (c) the freezing of undercooled droplets in the atmosphere.

G-18. Findeisen, W.: Die Kolloidmeteorologischen Vorgänge bei der Niederschlagsbildung. (The Colloidal-Meteorological Process in the Formation of Precipitation.) Meteorol. Zeitschr (Brunswick), Bd. 55, April 1938, pp. 121-133.

G-19. Fluid Motion Panel of the Aeronautical Research Committee and Others: Modern Developments in Fluid Dynamics. Vols. I and II, S. Goldstein, ed., The Clarendon Press (Oxford), 1938.

*G-20. Findeisen, W. (J. Vanier, trans.): Meteorological-Physical Limitations of Icing in the Atmosphere. NACA TM 885, 1939. 7 pp., 8 figures. A general discussion of cloud temperatures, moisture content, types of clouds, and precipitation. Author supports the Borgeron theory.

G-21. Findeisen, W.: Flugmeteorologische Schneebeobachtungen. (Flight Meteorological Observations of Snow.) Meteorol. Zeitschr. (Brunswick), Bd. 56, 1939, pp. 429-433.

G-22. Flora, S. D.: Nature's Pranks Are His Hobby. Taylor-Rochester, vol. 29, 1939, pp. 41-45.

G-23. Volmer, Mat: Kinetik der Phasenbildung. (Kinetics of Phase Formation.) Theodor Steinkopff (Dresden und Leipzig), 1939.

1940 - 1950

*G-24. Stickley, A. R.: An Evaluation of the Bergeron-Findeisen Precipitation Theory. Monthly Weather Rev., vol. 68, no. 10, Oct. 1940, pp. 272-280. 15 figures, 3 tables, 27 references.

G-25. Bricard, J.: Contribution a l'étude des brouillards naturels. Annales de Physique (Paris), 11e série, tome 14, 1940, pp. 148-236.

G-26. Krastanow, L.: Über die Bildung der unterkuehlten Wassertropfen und der Eiskristalle in der freien Atmosphäre. (On the Formation of Supercooled Water Drops and Ice Crystals in the Free Atmosphere.) Meteorol. Zeitschr. (Brunswick), Bd. 57, 1940, pp. 357-371.

*G-27. Anon.: Pre-Coldfrontal Squall Lines. Meteorology Circular No. 16, Meteorology Department, United Air Line Transport Corp. (Chicago), March 1, 1941, 12 pp. 3 figures, 2 tables. A good discussion of the squall lines that develop east of the Rockies and the results of a study of all squall lines occurring near the Cheyenne-New York airway between April 1939 and May 1940.

*G-28. Shipley, J. F.: The Air Currents in a Lightning Storm. Quarterly Jour. Roy. Meteorol. Soc., vol. 67, Oct. 1941, pp. 340-345. A discussion of thunderstorm circulation from central heating to dissipation.

G-29. Krastanow, L.: Beitrag zur Theorie der Tropfen und Kristallbildung in der Atmosphäre. (Contribution to the Theory of Water Drop and Ice Crystal Formation in the Atmosphere.) Meteorol. Zeitschr. (Brunswick), Bd. 58, 1941, pp. 37-44.

*G-30. Brancato, George N.: The Meteorological Behavior and Characteristics of Thunderstorms. Hydrometeorological Sections, U. S. Weather Bur., April 1942, 16 pp. Because some thunderstorms cause flooding, the Hydrometeorological Section of the U. S. Weather Bureau was assigned the problem of determining the depth-frequency-elevation relationship and areal extent of the thunderstorm. As a result of this study, it became possible to form conclusions concerning other thunderstorm characteristics. This paper discusses the conclusions reached and compares them with the conclusions reached by Humphreys, Petterssen, and Shaw.

*G-31. Weickmann, Helmut: Experimentelle Untersuchungen zur Bildung von Eis und Wasser an Keimen bei tiefen Temperaturen und ihre Folgerungen bezülg. des Wachstums der atmosphärischen Eiskristalle. (Experimental Investigations in Formation of Ice and Water Nuclei at Low Temperature and Conclusions Drawn from Them with Respect to the Growth of Atmospheric Ice Crystals.) Forschungsbericht Nr. 1730, ZWB, Berlin-Adlershof, Nov. 18, 1942, 81 pp. Translated in Harvard-Mount Washington Icing Research Report 1946-1947, Tech. Rep. No. 5676, AMC, USAF (Dayton, Ohio), June 22, 1948, pp. 484-594. 60 figures, 40 references.

*G-32. Workman, E. J., Holzer, R. E., and Pelsor, G. T.: The Electrical Structure of Thunderstorms. NACA TN 864, 1942. 47 pp., 6 tables, 16 figures. The time history of thunderstorm charge distribution is given for three storms occurring during the summer of 1940 in the vicinity of Alberquerque. Horizontal and vertical cross-sectional diagrams are presented.

G-33. Diem, M.: Messungen der Grösse von Wolken-elementen. (Measurements of the Magnitude of Cloud Elements.) Annalen Hydrographic und Maritimen Meteorologie (Hamburg), Bd. 70, 1942, pp. 142-150; pt. 2 in Meteorol. Rundschau (Berlin), Bd. 1, Heft 9-10, 1948, pp. 261-273. Includes discussion on cloud droplet size distribution.

*G-34. Buell, C. E.: The Determination of Vertical Velocities in Thunderstorms. Bull. Am. Meteorol. Soc., vol. 24, no. 3, March 1943, pp. 94-95. 2 tables. Method of calculating the vertical veloity in thunderstorms.

*G-35. Stanley, R. M.: Cumulonimbus Hazard to Aircraft. Bull. Am. Meteorol. Soc., vol. 24, no. 5, May 1943, pp. 213-214. The author gives some of his experiences with cumulonimbus clouds during soaring flights.

G-36. Krastanow, L.: Über die Bildung und das Wachstum der Eiskristalle in der Atmosphare. (On the Formation and Growth of Ice Crystals in the Atmosphere.) Meteorol. Zeitschr. (Brunswick), Bd. 60, 1943, pp. 15-25.

*G-37. Kaster, H. B.: Lightning Strikes and Static Discharges. UAL Meteorology Circular No. 24, Meteorology Dept., United Air Lines, Inc. (Chicago), March 1, 1944, 3 pp. Brief description of the sequence of events leading up to a lightning discharge, including radio static, coronal discharge, turbulence, precipitation, and so forth. Points out the best methods of avoiding lightning strikes.

*G-38. Anon.: Forecasting Thunderstorms by the Slice Method. Rep. No. 798, Weather Div., Headquarters Army Air Forces (Washington), Aug. 1944, 43 pp., 12 figures. Part I - Determination of atmospheric stability by the slice method by N. R. Beers. Part 2 - Some examples of the application of the slice method of thunderstorm forecasting. In three pages specific examples are discussed.

G-39. aufm Kampe, H. J.: Sichtweite und Wassergehalt in Wolken. (Visibility and Water Content in Clouds). UM Nr. 3541, ZWB, Berlin, Sept. 13, 1944. Translation in Monthly Res. Bull., Mt. Washington Observatory, vol. 2, no. 9, Sept. 1946.

G-40. Bickenbach, A., and Weickmann, H.: Die Reichweite verschiendener Waermepeilgeraete im Nebel, UM Nr. 3556, ZWB, Berlin, 1944.

G-41. Krastanow, L.: Bemerkungen zur Klaerung des Problems der Atmosphärischen Eisteilchenbildung. (Remarks Regarding the Classification of the Problem of Atmospheric Ice Particle Formation.) Meteorol. Zeitschr. (Brunswick), Bd. 61, 1944, pp. 19-26.

G-42. Weickmann, Helmut: Formen und Bildung Atmosphärischen Eiskristalle. (Shapes and Formation of Atmospheric Ice Crystals.) Beitrage zur Physik der Freien Atmosphare (Leipzig), Bd. 28, 1945, pp. 12-52. (Available U. S. Weather Bur. Lib.)

*G-43. Beers, Norman R.: Thunderstorms and the Freezing Level. Bull. Am. Meteorol. Soc., vol. 27, no. 2, Feb. 1946, pp. 54-58. 2 figures, 10 references. Discusses the hail stage in the abiabatic process.

*G-44. Harrison, L. P.: Lightning Discharges to Aircraft and Associated Meteorological Conditions. NACA TN 1001, 1946, 149 pp., 13 figures, 33 references. Extensive summary report of available information for the NACA Subcommittees on Lightning Hazards to Aircraft.

G-45. Anon.: First Technical Report under Signal Corps Contract. Weather Radar Research Dept. of Meteorology, M.I.T. (Cambridge), Dec. 31, 1946.

G-46. Ryde, J. W.: The Attenuation of Centimeter Waves and Echo Intensities Resulting from Atmospheric Phenomena. Jour. Institution of Electrical Engineers (London), vol. 93, pt. III A, 1946, pp. 101-103.

*G-47. Schaffer, W.: Inclined Streamline Flow. Quarterly Jour. Roy. Meteorol. Soc., vol. 72, nos. 312-313, April-July 1946, pp. 235-250. 11 figures. Equations of motion for air-currents flowing at an angle to the horizontal are derived. From these, an equation is developed relating the veering or backing of the wind with height to the rate of ascent of the air and the local rate of rise of temperature.

*G-48. Johnson, Sir Nelson K.: The Work of the British Meteorological Research Committee. Bull. Am. Meteorol. Soc., vol. 28, no. 2, Feb. 1947, p. 93. Research activity supports Humphrey's theory on hail formation.

*G-49. Stommel, Henry: Entrainment of Air into a Cumulus Cloud. Jour. Meteorology, vol. 4, no. 3, June 1947, pp. 91-94. 6 figures, 1 table, 4 references. A theoretical analysis of convective cloud formation is presented; the fundamental hypothesis being that the ascending current in a cloud entrains air from its surroundings.

*G-50. Langmuir, Irving: Summary of Results Thus Far Obtained in Artificial Nucleation of Clouds. First Quarterly Progress Rep. Project CIRRUS, General Electric Research Lab. (Schenectady), July 15, 1947, pp. 4-11. Includes discussion of the evaporation-condensation theory of the growth of small droplets and describes their study of ice crystal growth within clouds.

*G-51. Schaefer, Vincent J.: Properties of Particles of Snow and the Electrical Effects They Produce in Storms. Trans. Am. Geophysics Union (Washington), vol. 28, no. 4, Aug. 1947, pp. 587-614. 8 tables, 16 figures, 18 references. This paper describes studies of the physical properties of snow crystals including their electrical characteristics. Measurements of falling velocity, quantity and sign of electric charge, mass, range in quiet air, variety of crystal forms, and other properties of single crystals are given.

*G-52. Marshall, J. S., Langille, R. C., and Palmer, W. McK.: Measurement of Rainfall by Radar. Jour. Meteorology, vol. 4, no. 6, Dec. 1947, pp. 186-192. 6 figures, 9 references. A mathematical discussion of the measurement of 10-centimeter radar echoes. The work reported was a part of a larger project undertaken by the Canadian Army Operational Research Group.

*G-53. Coons, Richard D.: Guided Propagation of Radar in Thunderstorm Conditions. Bull. Am. Meteorol. Soc., vol. 28, no. 7, Sept. 1947, pp. 324-329. 8 figures. Includes pictures of PPI radar scope during thunderstorm activity.

*G-54. Schaffer, W.: The Thunderstorm High. Bull. Am. Meteorol. Soc., vol. 28, no. 8, Oct. 1947, pp. 351-355. 4 figures. Discussion and theoretical consideration of the frequent tendency for pressures to rise during thunderstorm precipitation and for pressures to fall again after the passage of the storm.

*G-55. Findeisen, W., and Schulz, G.: Experimental Investigations Relating to the Formation of Ice Particles in the Atmosphere. Translation No. 387, U. S. Air Force, Dec. 5, 1947, 45 pp. From Forschungs und Erfahrungsberichte des Reichsivetterdienstes (Berlin), 1944. Direct measurements of temperature, water content, and ice content made in various cloud formations and laboratory tests, showed that ice formation in a cloud is a gradual process. The first solid particles form on a certain class of nuclei when a critical temperature is reached. As the temperature is further reduced, more and different atmospheric impurities act as nuclei. This first ice formation is a direct sublimation of the water vapor to a solid. The vertical velocity of the cloud mass determines the critical temperature required.

G-56. Wexler, Raymond, and Weinstein, Joseph: Rainfall Intensities and Attenuation of Centimeter Electromagnetic Waves. Proc. Inst. Radio Engineers (New York), March 1948.

*G-57. Langmuir, Irving: The Production of Rain by a Chain Reaction in Cumulus Clouds at Temperatures above Freezing. Occasional Rep. No. 1, Project CIRRUS, General Electric Research Lab. (Schenectady), April 15, 1948, 26 pp., 13 tables. Discusses (a) evaporation-condensation theory of cloud droplet growth, (b) terminal velocity of a falling drop, (c) types of rain and snow in relation to spontaneous and to artificial seeding, (d) chain reaction in snow and rain formation.

*G-58. Howell, Wallace E., and others: Harvard-Mount Washington Icing Research Rep. 1946-1947. Tech. Rep. No. 5676, A.M.C. USAF (Dayton, Ohio), June 22, 1948, 802 pp. A collection of

28 research reports which may be classed under the following general topics: (a) the relation of icing to the synoptic weather situation, (b) studies of the statistical expression of underlying physical relationships among the factors affecting icing, (c) development and evaluation of instruments and instrumental techniques in the measurement of icing phenomena, (d) physical characteristics of icing clouds and ice accumulations.

*G-59. Smith-Johannsen, Robert: Some Experiments on the Freezing of Water. Occasional Rep. No. 3, Project CIRRUS, General Electric Research Lab. (Schenectady), June 1, 1948, 7 pp. Water samples were frozen in a special container arranged in such a way that no air-solid interface below 0° C was in contact with the liquid. The surface of the liquid was exposed to the air. Under these conditions, it was found that water normally freezes at approximately -20° C. However, water which had been exposed to ultrasonic radiation froze in one case at -38.5° C.

*G-60. Byers, Horace R., and Braham, Roscoe R., Jr.: Thunderstorm Structure and Circulation. Jour. Meteorology, vol. 5, no. 3, June 1948, pp. 71-86. 23 figures, 16 references. Analysis of the data obtained from the thunderstorm project show that the thunderstorm is composed of several distinct cells and that each cell has a three-stage life cycle. Entrainment of air into these cells, combined with convection, results in lapse rates in the updraft and downdraft regions that approximate the lapse rates of the environment.

*G-61. Vonnegut, Bernard: Occasional Rep. No. 5. Project CIRRUS, General Electric Research Lab. (Schenectady), July 15, 1948, 12 pp., 6 figures. Discusses (a) production of ice crystals by the adiabatic expansion of gas, (b) nucleation of supercooled water clouds by silver-iodide smokes, and (c) influence of Butyl alcohol on shape of snow crystals formed in the laboratory.

*G-62. Loughborough, Dwight L., Greene, Howard E., and Roush, Paul A.: A Study of Wing De-Icer Performance on Mount Washington. Aero. Eng. Rev. (New York), vol. 7, no. 9, Sept. 1948, pp. 41-50. 21 figures, 18 references. Gives data concerning tensile strength and adhesion of ice compared to the density of the ice.

*G-63. Weickmann, H. (M. G. Sutton, trans.): The Ice Phase in the Atmosphere. (Die Eisphase in der Atmosphare.) Library Translation No. 273, Royal Aircraft Establishment, Ministry of Supply, Millbank, (London), Sept. 1948, 95 pp. 42 figures, 50 plates, 68 bibliography. Reports the results of 6 years of research on the formation, appearance, occurrence, and growth of the ice

phase in the laboratory, on the ground, and in the atmosphere up to altitudes of 32,500 feet. The most important result is the theoretical and experimental proof that no sublimation nuclei exist and that down to cirrus temperatures crystals form on freezing nuclei via the state of water saturation, or at least at ice supersaturation humidities.

*G-64. Blanchard, Duncan C.: Observations on the Behavior of Water Drops at Terminal Velocity in Air. Occasional Rep. No. 7, Project CIRRUS, General Electric Research Lab. (Schenectady), Nov. 1, 1948, 13 pp. Gives (a) experimental setup and results obtained, (b) size of drop and suspension times, (c) maximum drop diameter before breakup, (d) drops subjected to sudden change in air velocity, (e) drop deformation, (f) breakup fragments of individual drops, (g) aerodynamic effects as a cause of drop collision, (h) drop breakup by collision effects.

G-65. Hooper, J. E. N.: Measurement of Radar Echo Intensities from Precipitation. Telecommunication Research Establishment (England), Nov. 15, 1948, Rep. T 2116.

*G-66. Cunningham, Robert M., and Miller, Robert W.: Five Weather Radar Flights: Measurements and Analysis. Tech. Rep. No. 7, Weather Radar Research, Dept. of Meteorology, M.I.T., Dec. 1, 1948, 54 pp. 81 figures, 19 references. Since microwave radar is a radically new tool for the meteorologist, the Army Signal Corps initiated the Weather Radar Project at M.I.T. in 1946, with the broad objective of accurate measurement of weather conditions aloft. This report covers only observations where airborne measurements were accurately coordinated in space and time with ground radar observations and measurements. Five cases were selected illustrating five different types of weather situations. The report includes a description of the instruments and radar system used and the obervational procedures by which the data were obtained. Exceptionally well illustrated with graphs, diagrams, maps, photographs, and so forth. Hail occurs infrequently in the Boston area where the data were obtained and is only mentioned briefly in figures 7 to 9.

*G-67. Whiting, R. M.: A Method of Forecasting the Degree of Turbulence in Fronts and Line Squalls. Meteorol. Dept., Eastern Air Lines, Inc. (Atlanta, Ga.), 1948. 22 pp. U. S. Navy reprint NAVAER 50-IR-228, Chief Naval Operations (Washington), Nov. 1948. 11 figures. A general discussion of the causes of turbulence and a method of forecasting by means of an impact factor and a resistance coefficient resulting in a forecast of light, moderate, severe, and extremely severe. No mention of definition.

G-68. Wichmann, Heinz: Grundprobleme der Physik des Gewitters. Heft 1 of Physikalische Forschung, Herausgegeben Von Pascaul Jordan, Wolfenbütteler Verlagsanstalt (Hannover), 1948, 118 pp. On thunderstorms with emphasis on electricity.

*G-69. Schaefer, Vincent J.: The Detection of Ice Nuclei in the Free Atmosphere. Occasional Rep. No. 9, Project CIRRUS, General Electric Research Lab. (Schenectady), Jan. 15, 1949, 5 pp., 3 tables, 3 figures. Results of supercooled cloud experiments in cold chamber - variation in number of sublimation nuclei as a function of free-air temperature - snow-flake formation.

*G-70. White, F. C.: A Summary of the "In-Flight" Dangerous Weather Avoidance Phase of the Navy-American Airlines Airborne Radar Flight Evaluation Program. A paper presented before the 101st Annual Meeting of the Am. Meteorol. Soc., Jan. 28, 1949, 7 pp., 14 pictures, 3 graphs. Pictures include radar installation, the NACA rotating cylinder ice-accretion meter and the radar scope showing cumulus clouds when ice was encountered.

*G-71. Schaefer, Vincent J.: The Possibility of Modifying Lightning Storms in the Northern Rockies. Occasional Rep. No. 11, Project CIRRUS, General Electric Research Lab. (Schenectady), Feb. 15, 1949, 12 pp. A study of cumulus clouds was made at the Priest River Forest and Range Experiment Station of the U. S. Forest Service. This location is in the center of a cloud breeding area where intense thunderstorms are frequent. The direct relation of cloud supercooling, ice-crystal concentration, thunderstorm intensity, lightning, and cloud modification by seeding are discussed.

*G-72. Bellamy, John C.: Objective Calculations of Divergence, Vertical Velocity and Vorticity. Bull. Am. Meteorol. Soc., vol. 30, no no. 2, Feb. 1949, pp. 45-49. 3 figures. Methods of calculating horizontal divergence, vertical velocities, and vorticity directly from wind observations without analyzing the wind field are presented.

*G-73. Byers, Horace R., and Hull, Edwin C.: Inflow Patterns of Thunderstorms As Shown by Winds Aloft. Bull. Am. Meteorol. Soc., vol. 30, no. 3, March 1949, pp. 90-96. 9 figures, 9 references. The thunderstorm project over Florida found that in the early stages of development, inflow or horizontal convergence is present at the ground as well as all heights reached by the cloud. In the mature stage, outflow or horizontal divergence was observed under the cloud base and again in the uppermost levels. Relationships to rainfall and to cloud entrainment of environmental air are shown.

*G-74. Workman, E. J., and Reynolds, S. E.: Electrical Activity As Related to Thunderstorm Cell Growth. Bull. Am. Meteorol. Soc., vol. 30, no. 4, April 1949, pp. 142-144. 1 figure. The authors investigated 12 thunderstorms by correlating electrical activity with visual observations of cloud development and with the internal structure of the cloud as presented by 3-centimeter radar.

*G-75. Heverly, J. Ross: Supercooling and Crystallization. Trans. Am. Geophysics Union (Washington), vol. 30, no. 2, April 1949. pp. 205-210; discussion by John C. Johnson and the author in vol. 31, no. 1, Feb. 1950, pp. 123-126. 3 figures, 21 references. Crystallization experiments were conducted in a laboratory, and the supercooling of water droplets was quantitatively studied under simulated atmospheric conditions. The spontaneous freezing point is presented in a graph as a function of droplet size.

*G-76. Byers, Horace R., and Battan, Louis J.: Some Effects of Vertical Wind Shear on Thunderstorm Structure. Bull. Am. Meteorol. Soc., vol. 30, no. 5, May 1949, pp. 168-175. 7 figures, 10 references. Observations of thunderclouds obtained with a 3-centimeter height-finding radar set are used to obtain a description of the vertical shear of thunderclouds. Several photographs are given which show the shearing of the radar cloud. Scattergrams of wind shear plotted against echo shear are given.

*G-77. Anon.: The Thunderstorm. Rep. of the Thunderstorm Project. Weather Bureau, U. S. Dept. of Commerce (Washington), June 1949, 287 pp., 254 figures, 49 tables. Final and complete report of the Thunderstorm Project. Hail in conjunction with thunderstorms in Florida and Ohio is discussed on pages 48 and 138.

*G-78. Katzin, M.: The Present Status of Weather Radar Research. Symposium on Tropospheric Wave Propagation, U. S. Navy Electronics Lab. (San Diego, Calif.), July 25-29, 1949, pp. 127-130. A review of the activities at the Massachusetts Institute of Technology and at the Naval Research Laboratory.

*G-79. Press, H., and Thompson, J. K.: An Analysis of the Relation between Horizontal Temperature Variations and Maximum Effective Gust Velocities in Thunderstorms. NACA TN 1917, 1949, 11 pp., 4 tables, 1 figure. Results indicate that the relation when extended to include frontal conditions appears useful for forecasting the intensity of turbulence for thunderstorms in temperate regions.

*G-80. Ayer, R. W., and White, F. C.: Development of an Airborne Radar Method of Avoiding Collisions with Terrain, Aircraft and Other Obstacles. Final Rep. on Test No. 2 of Navy BuAer Contract NO a(s)-9006, Operational Development Branch, Flight Engineering, American Airlines System (New York), Sept. 15, 1949, 13 pp., 4 figures. Several descriptions of the X-band airborne radar used on this project to ascertain its usefulness in terrain and weather avoidance.

*G-81. Blanchard, Duncan C.: Experiments with Water Drops and the Interaction between Them at Terminal Velocity in Air. Occasional Rep. No. 17, Project CIRRUS, General Electric Research Lab. (Schenectady), Dec. 15, 1949, 29 pp., 15 figures. Design of vertical wind tunnel; growth of water drops; water-drop breakup; circulation of water in a droplet falling at terminal velocity.

*G-82. Workman, E. J., and Reynolds, S. E.: Time of Rise and Fall of Cumulus Cloud Tops. Bull. Am. Meteorol. Soc., vol. 30, no. 10, Dec. 1949, pp. 359-361. Observations were made for the purpose of correlating the electrical activity of thunderstorms to the growth of individual cells. Gives the average time of ascent and descent of 47 cloud tops.

*G-83. Chalmers, J. Alan: Atmospheric Electricity. Oxford Univ. Press (London), 1949, 175 pp. Brief note on the charges on snow, sleet, and hail on pp. 116-117. 13 references cited in regard to these charges.

G-84. Orr, John L.: Analysis of Experiments of Inducing Precipitation. Report No. MD-32, National Research Council of Canada (Ottowa), 1949.

*G-85. Schaefer, Vincent J.: The Occurrence of Ice Crystal Nuclei in the Free Atmosphere. Occasional Rep. No. 20, Project CIRRUS, General Electric Research Lab. (Schenectady), Jan. 15, 1950, 24 pp., 7 figures. Gives the results of a study of sublimation nuclei, necessary to form ice crystals. Observations were taken at Mt. Washington Observatory during periods of high sublimation nuclei counts.

*G-86. Mason, B. J.: The Nature of Ice-Forming Nuclei in the Atmosphere. Quarterly Jour. Roy. Meteorol. Soc., vol. 76, no. 327, Jan. 1950, pp. 59-74. 1 figure, 1 table, 31 references. During the last decade many experiments have been designed to investigate the initial processes of ice formation in the atmosphere. The results of these experiments are examined for clues as to the identity of the responsible nuclei and the following tentative conclusions are reached: (a) The nuclei which cause freezing

between 0° C and -32° C are mainly solid, insoluble particles which are melted by water and produce ice crystals by the freezing of water drops. (b) The nuclei which become operative in the range -32° C to -41° C consist of droplets of sea salt solution, ice and salt crystallizing out on contaminating foreign particles. (c) The nuclei effective at just below -41° C consist of droplets of "pure" salt solution and possibly of "gaseous" nuclei formed industrially or by the action of ultraviolet light on gases of the upper atmosphere.

*G-87. aufm Kampe, H. J.: Visibility and Liquid Water Content in Clouds in the Free Atmosphere. Jour. Meteorology, vol. 7, no. 1, Feb. 1950, pp. 54-57; correction in vol. 7, no. 2, April 1950, p. 166. 6 figures, 15 references. Koschmieder's formula is verified by experimental data obtained on Mt. Washington and is used to determine visibility in clouds from measurements of the scattering coefficient. Knowing the visibility and drop size, it is possible to calculate the liquid water content by applying the Trabert formula. The average water content in large cumulus clouds is approximately $2.5 g/m^3$, in fair weather cumulus $0.5 g/m^3$ and in stratus $0.2 g/m^3$.

*G-88. Langmuir, Irving: Progress in Cloud Modification by Project CIRRUS. Occasional Rep. No. 21, Project CIRRUS, General Electric Research Lab. (Schenectady), April 15, 1950, 25 pp., 2 figures. Part I describes the effects of various seeding techniques on the growth modification of large cumulus clouds. Part II discusses the equation for determining the probability that a shower will occur at a definite place and time. The author shows that controlled seeding increases the probability of rainfall in New Mexico.

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NACA TN 2734
National Advisory Committee for Aeronautics.
SUMMARY OF AVAILABLE HAIL LITERATURE AND THE EFFECT OF HAIL ON AIRCRAFT IN FLIGHT.
Robert K. Souter and Joseph B. Emerson.
September 1952. 162p. diagrs., photos., 6 tabs.
(NACA TN 2734)

Available information on the hail phenomenon affecting aircraft in flight has been examined. This paper attemps to coordinate the present knowledge of hail with the effect of hail on aircraft in flight and includes (1) a digest of the literature on the physical properties, the occurrence, and the formation of hail; (2) a survey of the hail effect on aircraft in flight from analyses of 57 cases of airplanes damaged by hail; (3) a résumé of hail information for the benefit of pilots, forecasters, and ground operational personnel; and (4) an annotated hail bibliography of 552 articles for use of research personnel.

Copies obtainable from NACA, Washington

1. Ice Formation (6.2)
2. Safety (7.1)
3. Navigation (7.2)
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